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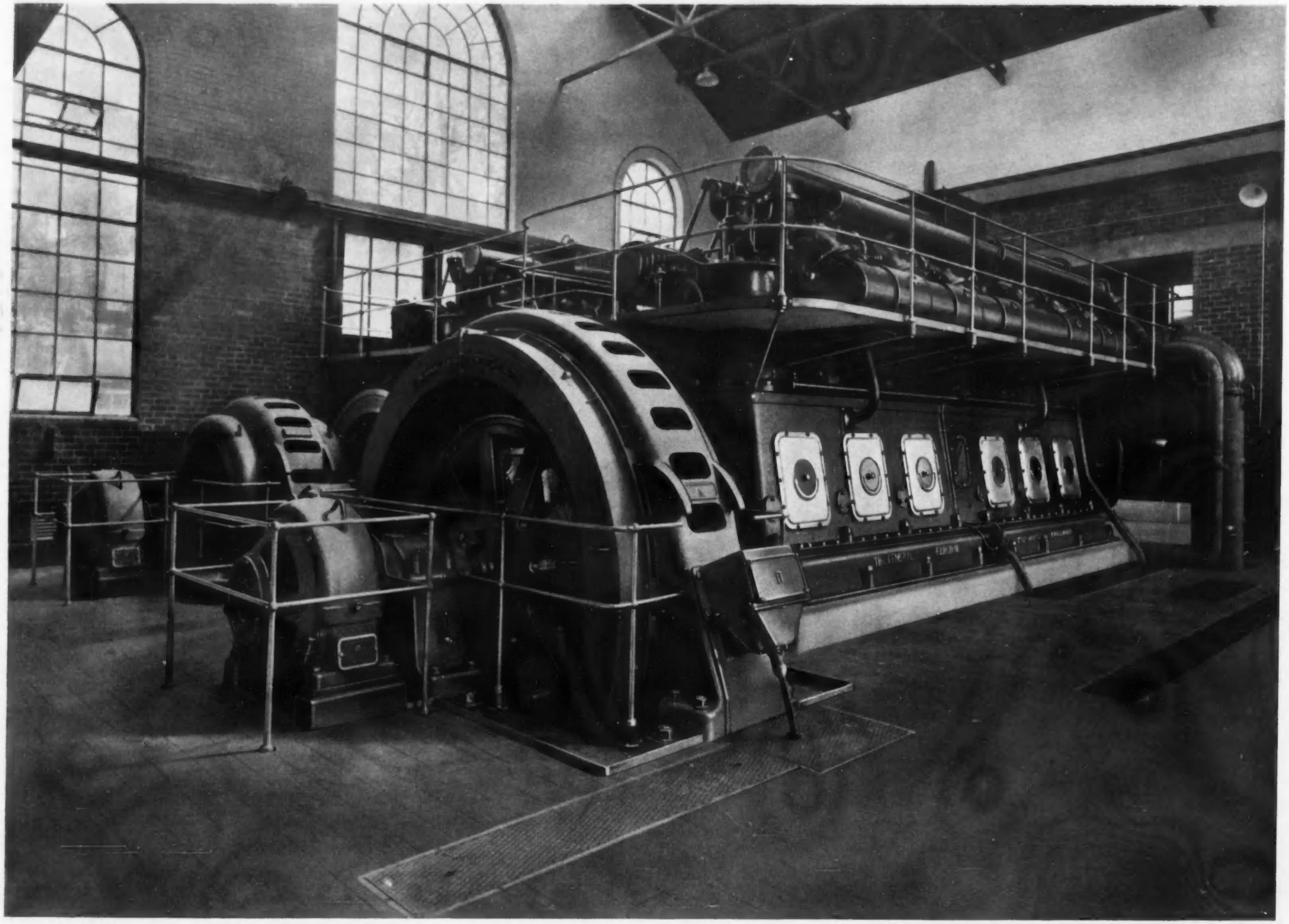

HAVERFORDWEST POWER STATION OF THE WEST CAMBRIAN POWER COMPANY.

In the foreground is a 6-cylinder 1,700 b.h.p. Fraser & Chalmers heavy oil engine driving a 1,500 kVA, 11,000 volt, 3-phase, 50 cycle G.E.C. alternator. The second set, partly seen in the background, is a 3-cylinder 850 b.h.p. heavy oil engine of the same make driving a 750 kVA alternator.

G.E.C. Journal

VOL. IV. AUGUST, 1933. No. 3.

Electric Hotplates.

By O. W. HUMPHREYS, B.Sc. and J. L. RYCROFT, B.Sc.

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In the following contribution the authors, after outlining the development of the electric hotplate and stating the factors determining its life and efficiency, proceed to discuss the relative advantages of the various types available.

An appendix is added in which full details are given of the methods of testing hotplates for life and efficiency.

THE TREND OF ELECTRIC HOTPLATE DESIGN.

IT is not proposed to attempt anything in the nature of a complete historical survey of hotplate development as this has already been done very adequately elsewhere.* It is interesting to recall, however, that the earliest hotplates were of the enclosed type and consisted of sheet metal tops with elements attached to their under surfaces. The insulating material most commonly employed was mica and in consequence the permissible wire temperature was seriously limited, loadings were low and performance, as judged by modern standards, very poor.

The desire for increased loadings led to the introduction of the open coil hotplate, in which the loading was limited only by consideration of the life of the resistor itself. It was very soon found that the new type of plate was too prone to damage through the boiling over of liquids to be considered satisfactory. Furthermore, the rapid boiling and high efficiency which were expected from the low thermal capacity of the open coil plate, were not obtained. Gradually the popularity of the open plate declined and attention was paid to improving the performance of the enclosed type of plate by using materials which would not be subject to the limitations of those previously employed.

The final breakaway from the open coil hotplate was started by the introduction from Switzerland of the enclosed hotplate in which the heating coil was embedded in an insulating refractory cement in grooves in a cast iron top. As first offered, this type of plate (which, for the sake of brevity, will be referred to simply as the cast iron hotplate) was very heavy, slow and inefficient, and its life, although a marked improvement on that of the open coil hotplate, still left a good deal to be desired. The general belief was that it would soon be superseded by something which, while still retaining the general advantages resulting from the protection of the element, would be very much lighter. Many such attempts have actually been made and a number of these lighter enclosed plates are available on the market to-day.

In parallel with this development work, however, further investigation had been proceeding in connection with the cast iron hotplate, which had resulted in a more complete understanding of the influence of various factors in design on performance and considerable improvements in the materials used. Consequently the performance of the cast iron top plate has been steadily improved and to-day cast iron hotplates are available which give boiling times 25 per cent shorter and lives at least 50 per cent longer than were obtainable 5 years ago. The marked favour with which hotplates of this type are now regarded is evidenced by the fact that they

* S. F. Bickell, Electrician Vol. 96, 1926, pages 350, 351 and 442, 448.

are now made by no less than four manufacturers in this country and are used, either exclusively or in very large quantities, by all cooker makers.

The question which naturally arises is whether the success of the cast iron hotplate is attributable to any fundamental superiority which it possesses over alternative forms of construction and the primary object of this article is to endeavour to find an answer to this question.

REQUIREMENTS OF AN ELECTRIC HOTPLATE.

To explain success, one must know the standards by which success is judged. A hotplate must pass three judges, the supply engineer, the householder, and the actual user, whose standards differ widely. The main interest of the supply engineer, apart from a desire to give satisfaction to his consumers, is that the hotplate should have as long a life as possible, so that his maintenance costs may be reduced to a minimum; the householder is most concerned in keeping his consumption of energy as low as possible, and he therefore looks for high efficiency; and the actual user, who is, of course, the cook, demands rapid boiling, both when the plate is new and throughout its life. Most types of hotplates would pass one of the three examiners.

The necessity cannot be too strongly emphasised when comparing hotplates, or designing new ones, of ensuring that all three of the above qualities are given due consideration, in order to ascertain that superiority in one direction has not been gained at the expense of sacrifices elsewhere. In particular it is necessary to bear in mind that any desired speed of boiling can be obtained by increasing loading at the expense of life.

FACTORS DETERMINING LIFE, EFFICIENCY AND SPEED OF BOILING.

In order properly to appreciate the factors by which life, efficiency and speed of boiling are determined, it might be remembered that any hotplate consists of two equally important components, namely the resistor, in which the electrical energy is converted into heat, and a mechanical component which acts primarily as a support for the resistor, but also serves as a support for the vessel. The failure of many of the hotplates which have been introduced in recent years must be attributed to the fact that the importance of the mechanical component has been underestimated. There has been a tendency to regard it as a necessary evil, which, by absorbing a great deal of the heat generated in the resistor, reduces efficiency, whereas in a well designed hotplate it may play an important part in facilitating the transfer of heat from the resistor to the vessel and thereby increasing efficiency. It is only by regarding the mechanical construction of the hotplate as of as much importance as the resistor that a thoroughly satisfactory hotplate can be obtained.

In what follows the two components will be referred to, for the sake of simplicity, as the resistor and the support, but it must be appreciated, of course, that the latter component will in the majority of cases, be a complex one.

The factors by which life, efficiency, and speed of boiling are determined can now be considered.

Life. The life of a hotplate must be regarded as terminated as soon as, for any reason whatsoever, its performance falls off to such an extent that it no longer gives satisfactory service to its user, and while life is most commonly ended by the failure of the resistor, fracture or serious distortion of the support must also be regarded as possible causes of failure. So far as the resistor itself is concerned, failure is usually due to oxidation. The rate at which oxidation takes place is determined by the composition of the wire used for the resistor, its temperature and the degree of exposure to the atmosphere, and the distance which the oxide has to penetrate before failure occurs. This latter factor is dependent on the wire diameter. In other words, for a given life a thick wire may operate at a higher temperature than a thin one, and a wire which is partially protected from the atmosphere may operate at a higher temperature than one which is not so protected. In addition to oxidation, failure of the resistor may occur as a result of chemical or electrolytic action between the resistor and some part of the support, movement of the coil, resulting in its coming into contact with an earthed part of the support, or breakdown at the joint between the resistor and the heavy end leads required for connecting the hotplate to the supply terminals.

Efficiency. The thermal efficiency of a hotplate is the ratio of the heat absorbed by the water to the thermal equivalent of the energy dissipated by the resistor. The major part of the heat which is not used for heating the water is either absorbed by the plate itself or radiated from its under surface and edges. In order to obtain maximum efficiency the sum of these two losses must be kept as small as possible. The actual efficiency obtained must obviously depend to a large extent on the vessel used, but a great deal can be done to increase efficiency by careful design of the hotplate itself, the important quantities being the thermal capacity of the hotplate, its mean temperature at the conclusion of the boiling operation and the temperature of its exposed surfaces.

Speed of Boiling. The speed of boiling is governed by the rate at which heat is transferred from the hotplate to the liquid which it is desired to boil. That is to say, it is directly proportional to the

product of loading and efficiency. The factors by which efficiency is controlled have already been discussed and it remains to consider the manner in which loading is limited. The first consideration is that the maximum temperature of the resistor must not exceed the value which is consistent with a satisfactory life, and the object of the designer is to obtain the highest possible loading consistent with the observance of this important requirement.

The loading is the product of the length of heating coil and the amount of energy which can be dissipated per unit length of coil. The length of coil is determined by a combination of geometrical, mechanical and electrical considerations, for the heating coil has to be distributed over the hotplate as uniformly as the dimensions of the latter permit; it must be well supported in a manner compatible with modern mass production manufacturing methods, and every part of it must be adequately insulated electrically, both from other parts of the coil itself, and from electrically conducting parts of its support. In order to obtain high energy dissipation without exceeding the permissible working temperature, the thermal resistance between the wire and the vessel must be reduced to a minimum. A further point to bear in mind is that an increase in the length of heating coil accommodated in the hotplate, besides being in itself a desirable feature, leads to an increase in wire diameter for a given resistance and hotplate loading, and therefore to an increase both in the amount of energy which can be dissipated per unit length of coil at a given temperature and also to an increase in the safe working temperature.

An intimate knowledge of the theoretical considerations which influence the various properties of hotplates will frequently be sufficient to enable one to determine which of two types is to be preferred, but in some cases practical tests will be required in addition. It is of the utmost importance that any tests shall be carried out under strictly controlled conditions, and some notes as to the points which require particular attention are given as an appendix to this article.

FUNDAMENTALS OF CONSTRUCTION.

A consideration of the above enables one to enumerate the following list of points, all of which should be taken into account when considering the relative merits of different types of hotplate construction :

(1) The length of wire used for the resistor.
(2) The proportion of the area of the hotplate covered by the resistor.
(3) The thermal resistance between the resistor and the vessel containing the water to be heated, or, in other words, the temperature gradient required between the resistor and the vessel for the transfer of a given amount of energy.
(4) The degree of protection of the resistor from the atmosphere.
(5) The strength of the support both when hot and when cold and its ability to withstand thermal shock resulting from cold liquids being poured on it when it is at its maximum temperature, and its ability to withstand long use, either with or without a vessel, without changing its shape in such a way as to affect the performance of the hotplate.
(6) The thermal capacity of the completed hotplate, its mean temperature at the end of the boiling operation and the temperatures reached by its exposed surfaces.
(7) In addition to the above attention should be paid to the following points which are independent of the general type of construction.

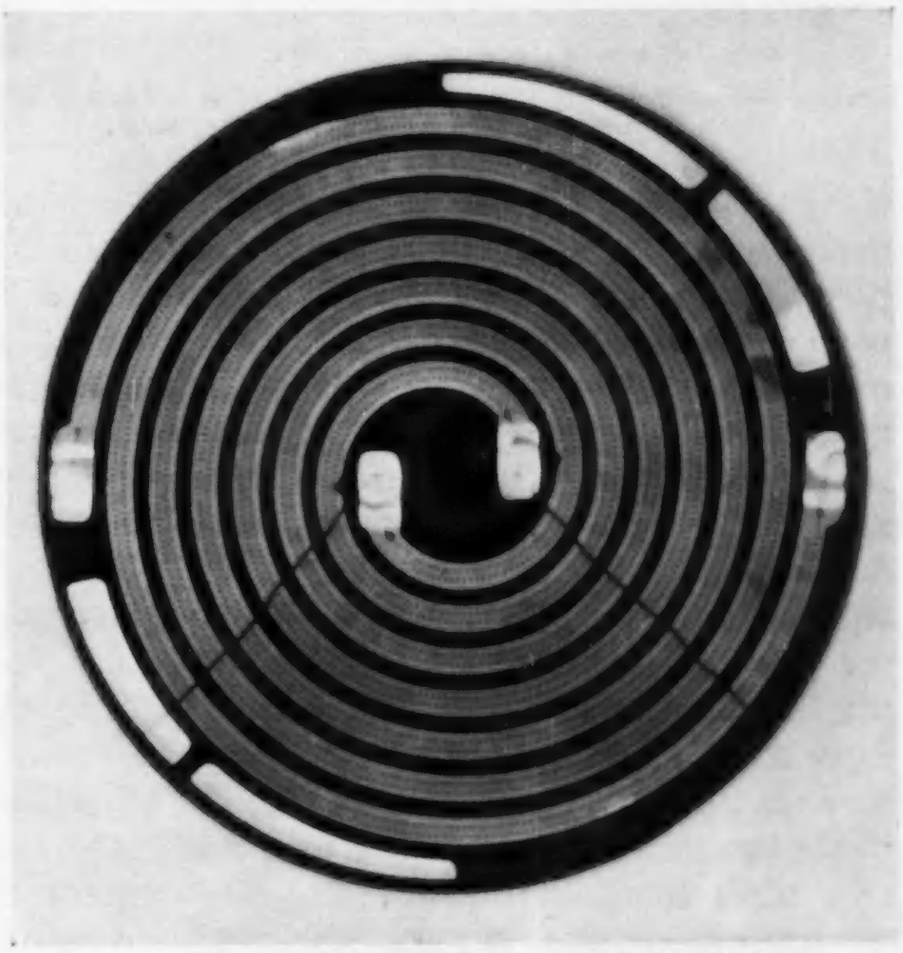


Fig. 1.—X-ray photograph of an 8 inch diameter Magnet hotplate.

(*a*) The nature of the joint between the resistor and the end lead.
(*b*) The nature of the materials used for the support and the possibility of their causing chemical or electrolytic corrosion of the resistor.

COMPARISON OF THE CAST IRON HOTPLATE WITH OTHER FORMS OF CONSTRUCTION.

We are now in a position to discuss the relative advantages of the cast iron and other forms of hotplate construction.

OPEN COIL HOTPLATES, HIGH VOLTAGE TYPE.

An advantage which the open coil hotplate possesses over all other types is that it can be so constructed as to have a very high insulation resistance.

As was stated in the introduction, its unpopularity was largely due to the fact that the coil was prone to damage, but, apart from this, there are a number of definite technical reasons why the performance of the cast iron plate should be superior.

The first of these is that in the cast iron plate, the resistor is so definitely held in position through-

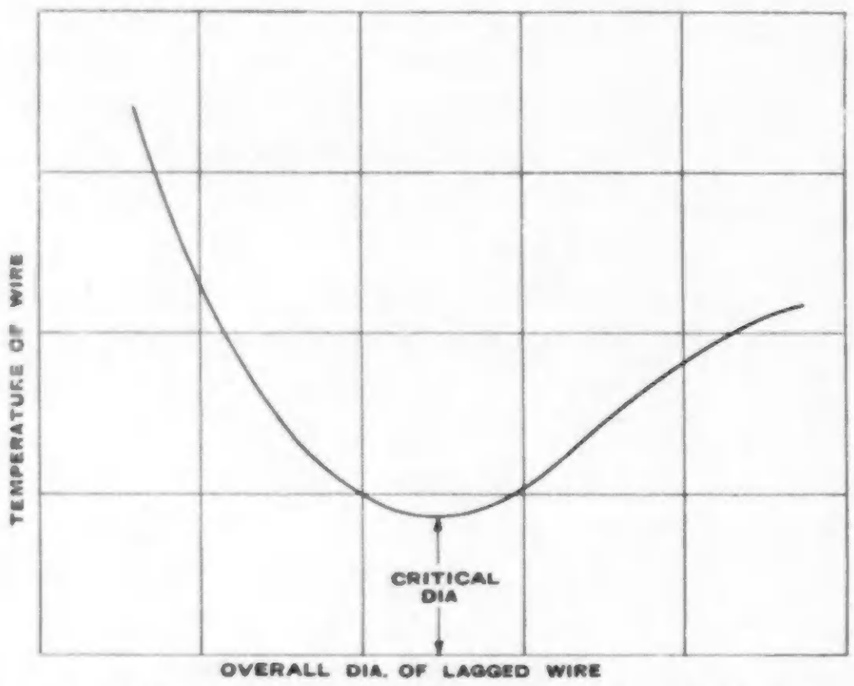


Fig. 2.—Variation of the temperature of a lagged wire with the overall diameter of the lagging.

out its whole length that clearances, both between the resistor and its support, and between adjacent parts of the resistor can be much smaller than is possible with a coil which is only supported at intervals. The very close spacing that can be safely achieved in the cast iron hotplate can be seen from fig. 1, which shows an X-ray photograph of an 8 in. diameter Magnet hotplate in which the distance between adjacent coils of the resistor is only about $\frac{1}{4}$ in. The second great advantage of the embedded construction arises from the fact that the amount of energy which can be dissipated from a wire for a given temperature difference between the wire and its surroundings is greater in the case of an insulated wire than it is in the case of a bare wire. Fig. 2 shows the relation between the temperature of a wire and the overall diameter of the insulating covering or lagging. The critical diameter "d" of the lagging corresponding to the minimum wire temperature varies with the insulating material; for magnesia "d" = 0.4 ins., while for glass "d" is about $6\frac{1}{2}$ ins. It follows that if the overall diameter of the covering of a wire is less than a particular value, it should be possible for a greater amount of energy to be dissipated per unit length of resistor for a given wire temperature if the resistor is embedded than would be possible if it were freely exposed. That this is actually the case can be very readily demonstrated by completely removing the refractory from about 1 in. of the groove, in a cast iron hotplate, thus leaving the coil exposed, removing a small amount of refractory from the part of the groove immediately adjacent to the part which has been cleared out, in such a manner as just to expose the outside of the coil and then putting the hotplate on circuit. When conditions have become steady, it will be obvious from visual inspection that the completely exposed part of the coil is operating at a very much higher temperature than the part which is embedded.

The third advantage of the embedded construction is that it definitely restricts, although it does not eliminate, the access of air to the heating coil. In consequence, the rate of oxidation is decreased and a higher operating temperature is permissible.

Summarizing the above, the cast iron hotplate is superior to the open coil hotplate, because it permits the use of a greater length of wire, a higher loading per length of wire for a given wire temperature, and a higher wire temperature for a given life. In the above discussion the hotplate has been regarded merely as a heater, and no allowance has been made for the fact that it will in general be in use with a vessel on its surface. It will now be interesting to consider what changes occur where a vessel is in use.

Any type of hotplate with no vessel on it loses its heat almost entirely by radiation to the surroundings, but when a vessel is in use, the heat transfer to the vessel will depend on the type of hotplate and may be by radiation, by conduction, or by a combination of the two methods. In the case of the open resistor hotplate, the heat transfer to the vessel is mainly by radiation, and the mean temperature of the vessel during the boiling operation is higher

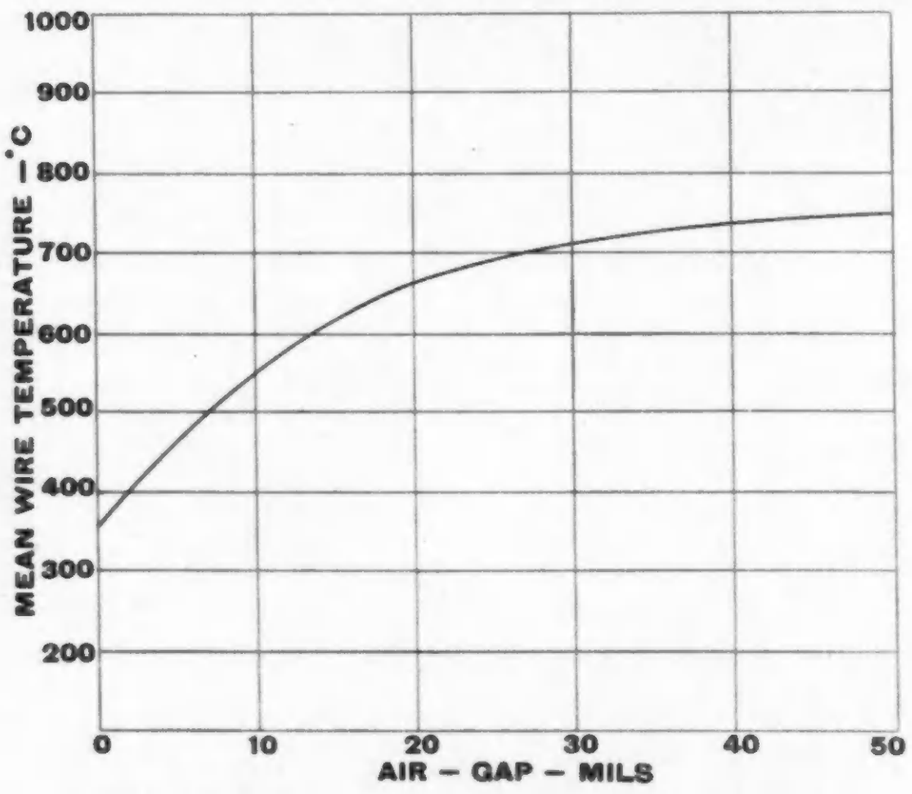


Fig. 3.—Relation between air-gap and mean wire temperature of 8 inch Magnet hotplate; loading 1,800 watts.

than that of the surroundings to which the hotplate radiates its heat when no vessel is in use. It follows that the wire temperature will be slightly higher when a vessel is in use than it is when the surface of the hotplate is uncovered, and the increase in temperature will be greater if a vessel having a reflecting bottom is used, since a large proportion

of radiation falling on it will be reflected back to the heating coil, thus causing still further increase in wire temperature. In the case of a cast iron hotplate the upper surface is flat and the major part of the heat is transferred to the vessel by conduction, either directly from metal to metal, or through the small air gap between the hotplate and the vessel bottom. The effect of this change in the mode of heat transfer is shown very strikingly by fig. 3, which shows the variation in mean wire temperature for an 1800 watt Magnet hotplate with the gap between the surface of the hotplate and the bottom of an aluminium saucepan having a machined bottom.* The temperatures given are the steady temperatures reached with water boiling in the saucepan. With the uniform gap over the whole surface of the plate of 50 mils., the wire temperature has approximately the same value as when no vessel is used. With a commercial machined bottom aluminium or cast iron vessel, the mean gap is of the order of 5 mils. of the inch, and the wire temperature is therefore approximately 270°C lower than it is when no vessel is in use. With a pressed aluminium vessel giving a mean gap of about 15 mils., the corresponding reduction in wire temperature is about 150°C. As the gap between vessel and hotplate increases the amount of heat transferred by radiation also increases, and for this reason if a vessel having a bottom with a high heat absorption coefficient were used the rate of temperature-rise with increasing gaps would be lower, and the gap required to give a wire temperature equal to that obtained with no vessel would be greater than was the case with the bright bottomed aluminium vessel.

vessel were used having a highly absorbing surface, and if a reflector having a high reflection coefficient were placed underneath the coil, the efficiency of the open coil plate should be high. In practice, however, it is difficult, if not impossible, to keep the

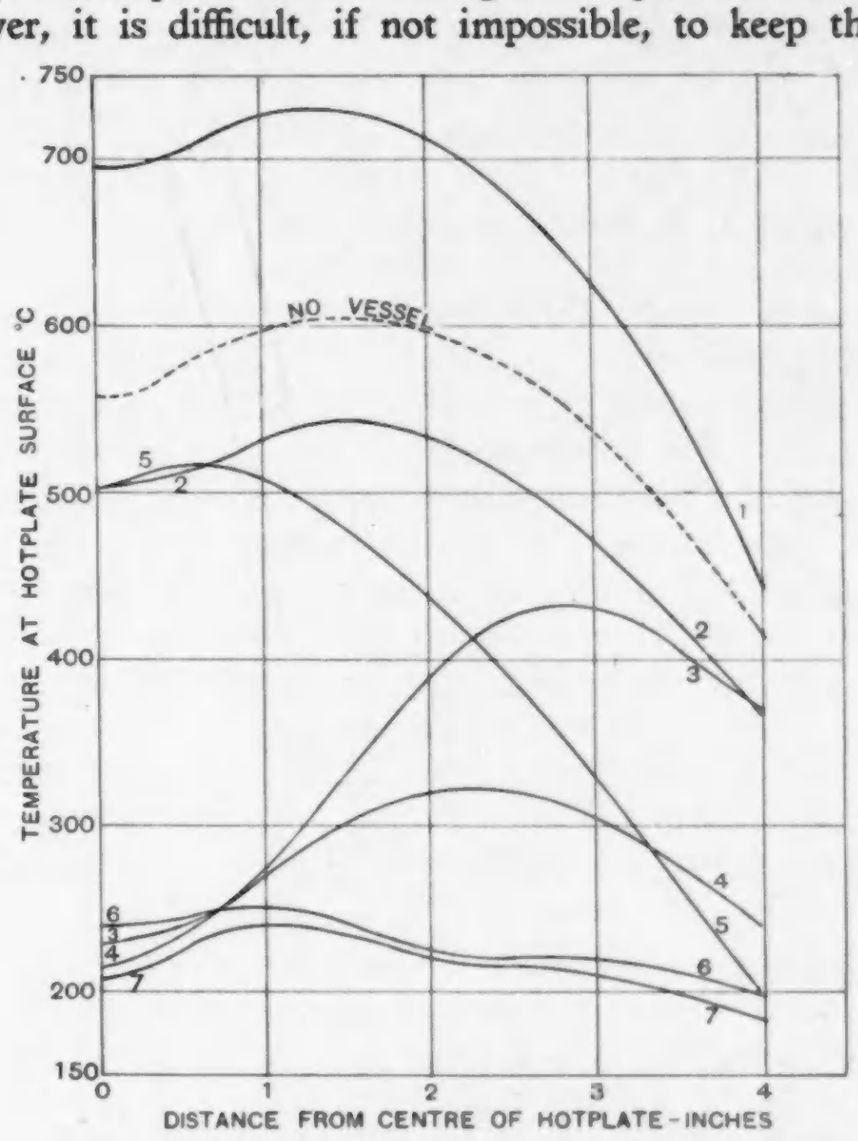


Fig. 4.—Variation of casting temperature with different vessels, using Magnet 8 inch hotplate, 1,800 watts.

1. Kettle with re-entrant bottom.
2. Enamelled iron pan.
3. Pressed aluminium pan with convex bottom.
4. Ordinary kettle with copper bottom.
5. Pressed aluminium pan with concave bottom.

6 and 7. Aluminium pans with machined bottoms.

Table I.

MAGNET HOTPLATES.

Boiling Times (85°C. Temp. rise) and efficiencies using machined bottom aluminium vessels.

Hotplate No.	Cat. No.	Size.	Loadings. Watts.			Surface Loading (Watts per sq. in. for "high" heat).	Boiling times from cold (mins.) and effcies. (%) with different quantities of water in a machined bottom aluminium saucepan.							
							1 pint.		2 pints.		3 pints.		6 pints.	
			High	Medium	Low		Boiling time (mins.)	Effcy. %	Boiling time (mins.)	Effcy. %	Boiling time (mins.)	Effcy. %	Boiling time (mins.)	Effcy. %
1	DC3739	8 11/16" dia.	2000	1000	500	33.7	5.75	29.2	7.7	43.8	9.7	52.0	15.3	66.1
2	DC3738	8" dia.	1800	900	450	35.8	4.9	38.2	7.5	49.8	9.4	59.7	15.7	71.3
3	DC3737	7 1/16" dia.	1200	600	300	30.6	7.3	38.5	10.3	54.5	13.5	62.5	—	—
4	DC3736	6 1/16" dia.	1000	500	250	32.0	8.3	40.5	12.4	54.0	15.7	64.5	—	—
5	DC3735	4½" dia.	450	—	—	28.3	14.5	51.5	—	—	—	—	—	—
6	DC3728	7¼" × 7¼"	1700	850	425	27.7	6.8	29.0	8.9	44.5	11.4	52.0	17.6	67.5
7	DC3729	7½" × 7½"	1700	850	425	30.0	6.1	32.5	8.4	47.0	10.5	56.5	17.1	69.5
8	DC3730	7" × 7"	1500	750	375	30.6	6.4	35.0	9.2	48.5	11.8	55.0	19.9	67.5
9	DC3731	8" × 5 11/16"	1500	750	375	31.6	7.4	30.5	10.2	44.0	12.8	52.5	20.6	65.5
10	DC3732	8½" × 5 11/16" ..	1700	850	425	33.7	7.3	27.1	9.9	40.6	12.1	49.1	18.9	62.6

It has been shown that the cast iron hotplate can be considerably more heavily loaded than the open coil plate to give the same life when used without a vessel, and that when used with a vessel, its life will be considerably longer in spite of its higher loading. The only point which remains to be considered is the question of efficiency. From theoretical considerations, it would appear that if a surface of a reflector bright, and in consequence, after a few month's use, the reflection coefficient of the reflector becomes very low. The position is worse still, of course, if an aluminium vessel be used, since in this case it is quite possible that more heat will be absorbed by and re-radiated from the underside of the reflector than will be absorbed by the bottom of the vessel.

That the efficiency of the cast iron hotplate is relatively high in spite of its considerable mass, is

* As the hotplate used for these experiments was in some respects special, the actual wire temperatures are somewhat different from what they would be in a standard Magnet Hotplate.

shown by the figures given in Table I. The explanation is to be found in fig. 4 which shows the temperature of the casting of a Magnet 8 in. diameter 1800 watt hotplate both when on circuit with no

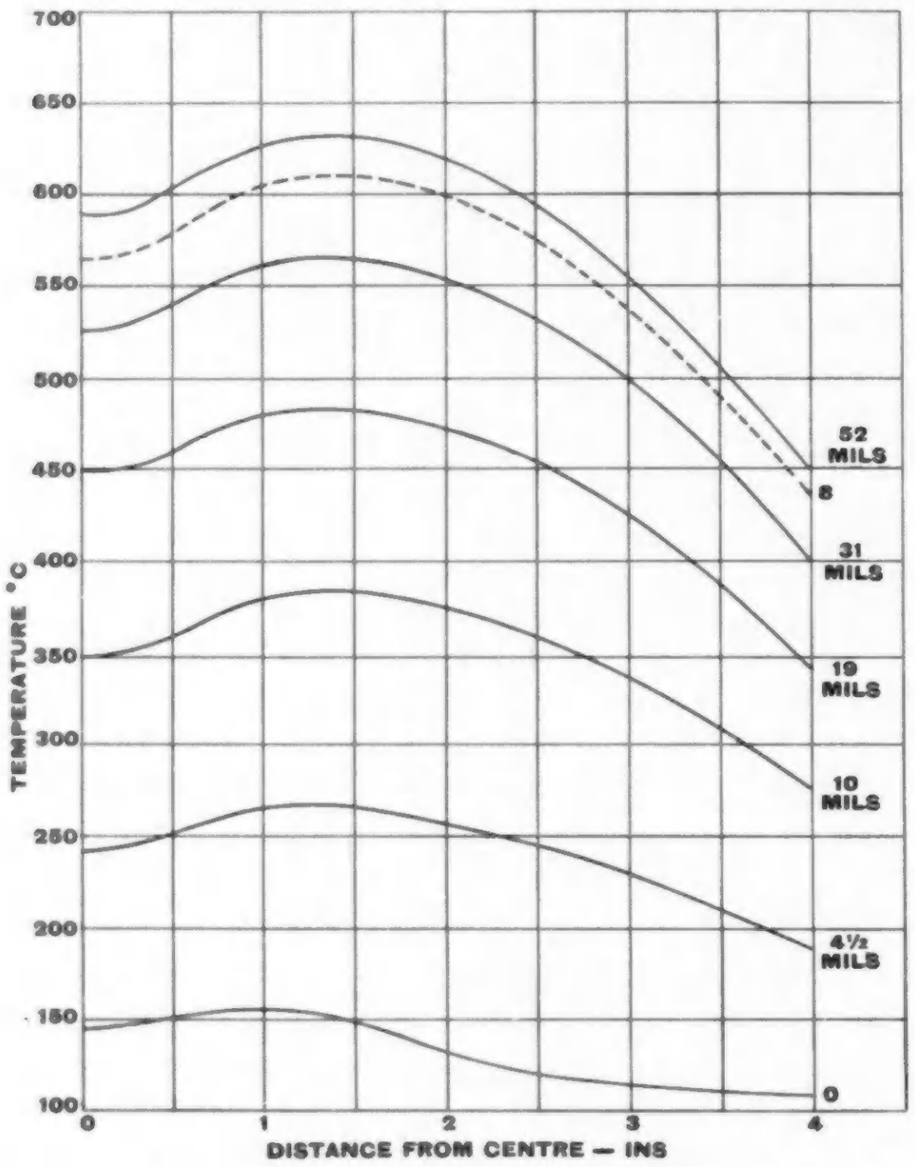


Fig. 5.—Relation between air-gap and casting temperature with Magnet 8 inch hotplate, 1,600 watts. The dotted line is with no vessel.

vessel and when in use with various kinds of utensils. The curves indicate that the temperature of the casting is lower when the hotplate is used with any of the types of vessel which are in common use in this country than it is when the surface of the hotplate is uncovered. Furthermore, if the vessel be one of the type which is specially made for use with electric hotplates of the enclosed type, the maximum casting temperature is only 250°C. and the average casting temperature is about 220°C. From this it follows that both the heat absorption and the heat radiation from the underside of the plate are very low. Fig. 5 is a companion to fig. 4 and shows the variation in the temperature of the casting with the gap between the hotplate and the bottom of an aluminium vessel with water boiling under steady conditions.

However high, initial efficiency is of no value unless it is maintained during life. Two factors might lead to a falling off in efficiency, namely, a decrease in the hotplate loading, and distortion of its surface.

Fig. 6 shows the average variation in loading with life for a batch of 5 Magnet hotplates which were tested under life test conditions, that is, one hour on circuit, half an hour off circuit, with no vessel in use, and it will be seen that the decrease in loading after 2000 hours under these conditions was only 25 watts.

A test under similar conditions was carried out with a view to determining the amount of distortion of the casting to be expected during life, and a result of this test is shown in fig. 7, from which it will be seen that the total distortion after 1000 hours on test under life test conditions was only 6 mils. and that the corresponding increase in boiling time, which is, of course, the thing which matters, was only about $\frac{1}{2}$ minute. In order to obtain this freedom from distortion during life, two precautions have to be taken. In the first place, the composition of the iron must be so chosen that repeated heating and cooling will not lead to any change in the composition of the iron, which would result in an increase in its volume, and secondly, the casting must be annealed at a temperature higher than the maximum temperature to which it will be heated in service, and subsequently machined.

So far as the ability of the casting to withstand thermal shock is concerned it is sufficient to record that, provided the composition of the iron is suitably selected, the castings can be heated up to a temperature of 700°C in a furnace and half immersed in water while at this temperature several times without becoming either distorted or fractured.

The only point which remains to be considered in connection with the cast iron hotplate is the nature of the joint between the resistor and end lead.

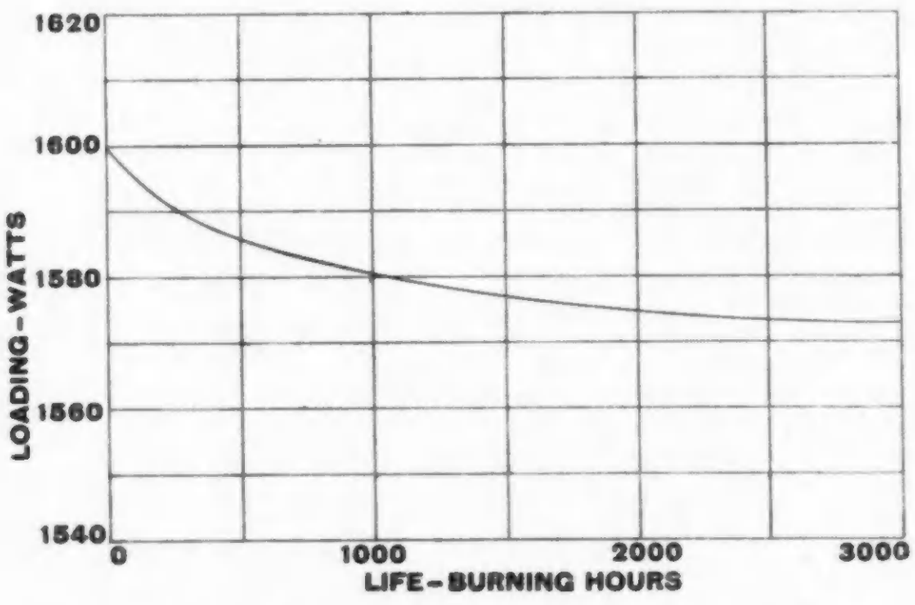


Fig. 6.—Average variation in loading with life for five 8 inch diameter hotplates.

There is no reason why any trouble whatsoever should be experienced at this point if the joint is made by welding, by a process which eliminates risk of overheating the relatively thin resistor wire, for with such a joint there is absolute continuity between resistor and end lead. Difficulties have been experienced however in some cases where a mechanical joint has been used owing to the oxidation of the various surfaces leading to an increase in

resistance which has resulted in the development of a "hot spot" at the joint and has ultimately caused a burn out at this point.

OPEN COIL HOTPLATES, LOW VOLTAGE TYPE.

The discussion of the open coil hotplate would be incomplete if no reference were made to the low voltage type of radiant plate employing a nickel chromium resistor of large cross sectional area fed from a transformer having a secondary voltage of the order of 10 volts. This construction has very many advantages over the high voltage open coil hotplate, the chief of which are that the element is very much more robust and a satisfactory life can be obtained with a considerably higher wire temperature. Actually the loading per unit area can be considerably higher than that of the cast iron type of plate and the brightly glowing resistor has a very great psychological appeal to some people. The effect of the high loading is offset however by very low efficiency, which is due in part to the causes discussed in connection with high voltage open coil plates and in part to the losses in the transformer and the leads from the transformer to the resistor. The highest efficiency which can be obtained with this type of hotplate for boiling 3 pints of water is only about 40 per cent whereas with a good cast iron hotplate an efficiency of 60 per cent can be obtained if flat bottomed utensils are used.

Comparing the low voltage radiation hotplate with the cast iron hotplate the former has the advantage of psychological appeal and relatively low cost of element replacement, while the latter is much more efficient, gives more rapid boiling with most kinds of vessel in spite of its lower loading, and has a much lower initial cost since no transformer is required.

EMBEDDED HOTPLATES WITH PLAIN (UNGROOVED) CAST IRON TOPS.

Consideration of this method of construction brings out an advantage resulting from the use of a grooved cast iron top which has not so far been considered, namely that the fins of iron which form the groove contribute very materially to the success of the cast iron hotplate. In the first place, they position the heating coils so definitely that the distance between coils can be reduced to a minimum, and in the second, they serve to conduct the heat from the underside of the coil to the hotplate casting, thus reducing the length of the refractory part through which this heat has to travel. This leads to decreased wire temperature, and also to a lowering of the temperature of the underside of the hotplate. The grooved top, as compared with the plain cast top, is therefore superior in that it can be more heavily loaded for a given wire temperature and life, and will also have a higher efficiency.

ENCLOSED HOTPLATES WITH SHEET METAL TOPS.

Hotplates in which the resistor is embedded in a refractory material but the hotplate top is of sheet metal instead of cast iron are included under this heading. This type of construction looks very attractive on account of the very considerable reduction in heat capacity which it permits, but it is subject to the inherent difficulty of obtaining good adhesion between refractory cements and sheet metals under the conditions encountered in the use of hotplates. The coefficient of expansion of refractory cements is very much lower than that of metals, and in consequence, when a hotplate is heated the metal top tends to break away from the refractory. If it succeeds in doing so there will thereafter be an air gap between the refractory and the top which will cause a considerable increase in the thermal resistance between the wire and the hotplate top with consequent increase in wire temperature accompanied by decrease in life. Now the only way of preventing this separation of the refractory from the metal is to ensure that the strength of the bond between these two materials is greater than that of the refractory itself. If this can be achieved the difference in expansion will be accommodated by a very minute separation between the particles of the refractory itself, and the adhesion between the metal and the particles of refractory in contact with it will not be broken. This end can only be attained by exercising great care in the choice of refractory and providing the surface of

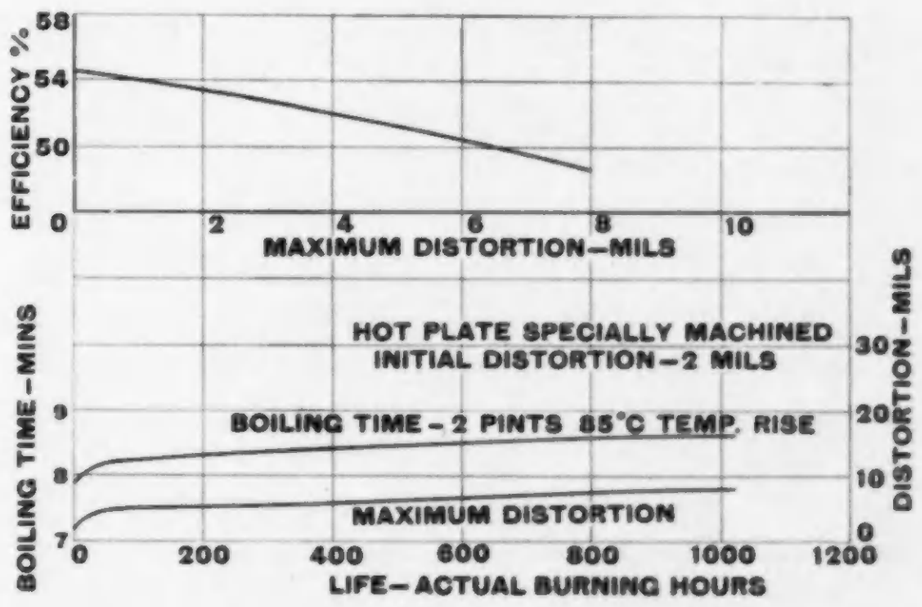


Fig. 7.—Distortion with life of 8 inch diameter hotplate, 1,600 watts. Hotplate on circuit with no vessel for 1 hour; off ½ hour.

the metal which is in contact with the refractory with a rough surface which will serve as a "key" for the refractory. Experience shows that the "as cast" surface of cast iron is excellent in this respect. The adhesion to a machined cast iron surface is not nearly so good as it is to the "as cast" surface, even if the machined surface is artificially roughened, and a great deal of experimental in-

vestigation has failed to reveal any way of obtaining anything approaching a satisfactory bond between sheet metal and refractory.

The presence of an air gap between the refractory and the sheet metal top leads not only to a higher wire temperature, but also to a higher refractory temperature and consequently to increased losses from the under surface of the hotplate, which largely counteracts, so far as efficiency is concerned, the advantage gained by low mass.

Sheet metal has the advantage over cast iron in that, as a result of its small mass, the cost of a sheet metal top made of a highly corrosion resistant material is considerably lower than that of a cast iron top providing an equal degree of resistance to corrosion. On the other hand cast iron is more robust and less likely to distort as the result of rough usage, and the presence of fins of iron between adjacent turns of the heating coils gives it an advantage as described above.

SHEATHED WIRE HOTPLATES.

The next type of hotplate to be considered is that which is commonly known as the sheathed wire hotplate. Two distinct methods of construction have been developed, one in America and the other in this country, but the appearance of the completed hotplates is the same. The finished element consists of a helical resistor embedded in magnesia in a heat resisting metal tube which is subsequently bent to the form required for the hotplate.

The sheathed wire hotplate is generally regarded as a radiation type plate and is the nearest high voltage equivalent to the low voltage open coil plate, which we have already discussed. It will be remembered that the latter hotplate was criticised on account of its high cost and low efficiency. The cost of the sheathed wire hotplate on the other hand, should be of the same order as that of any other embedded hotplate, and its efficiency is high since its heat capacity is low and the vessel can be placed in contact with the red hot sheath tube and therefore receives a considerable amount of heat by direct conduction. So long as the element remains flat high efficiencies are obtained with flat bottomed aluminium utensils but it is really preferable to use vitreous enamelled utensils since these will give high efficiencies both when the plate is new and when it becomes distorted, receiving heat, in the latter case, by conduction from those points of the element with which they are in contact and by radiation from the remainder. Pressed aluminium utensils, with bottoms which are not flat, are the least suitable for use with this type of hotplate as is shown by the figures in Table II.

Although superior to the low voltage open coil hotplate from the point of view of efficiency, the sheathed wire hotplate is very much inferior from the point of view of life. Heat is transmitted from the hotplate to the vessel by radiation because the surface temperature of the hotplate is high, in fact the visible evidence of heat is, to many people, the most attractive feature of this type of hotplate. Now with any embedded construction the temperature of the wire must obviously be higher than that of the surface of the hotplate, and, provided the thermal resistance between wire and surface is the same, the relation between wire temperature and surface temperature for different types of construction will not differ greatly. It follows therefore, from the very fact that the surface of the sheath tube reaches a higher temperature than that reached by the surface of the casting in a cast iron hotplate, that the temperature of the wire be higher in the sheathed element. The same conclusion is readily reached by somewhat different reasoning. The surface of the sheathed element reaches a higher temperature than that of the cast iron hotplate because, as the turns of the sheathed wire element are not contiguous, the area of its metal surface is lower than that of the casting, for a given size of hotplate, and consequently the energy dissipation per unit of surface area is higher. Now the fact that there are spaces between the turns of the sheathed element also necessitates the use of a shorter length of resistor coil than can be accommodated in a cast

Table II.

The effect of curvature and colour of the bottoms of vessels on boiling times for various types of hotplates.

Type of Hotplate.	Loading.	Boiling times (85°C. temperature rise) for 3 pints of water using vessels as stated.						
		Thin aluminium.				Heavy (machined bottom) aluminium.		Vitreous enamelled iron.
		Vessel A.		Vessel B.	Vessel C.	Under surface bright.	Under surface painted black.	Vessel D.
		Under surface bright.	Under surface painted black.					
	Watts.	Mins.	Mins.	Mins.	Mins.	Mins.	Mins.	Mins.
Cast Iron	1800	10.3	10.3	11.7	13.9	9.5	9.5	14.2
Low voltage radiant	2250	15.9	11.3	14.9	15.1	14.2	12.0	11.5
Sheathed Wire	1500	12.8	10.9	12.2	12.7	11.7	11.6	11.1

iron hotplate, and consequently the energy dissipation per unit length of coil is also higher, which again indicates that the wire temperature must be higher even if the surface area of the wire per unit length of coil is the same in both cases. Since the sheathed wire construction necessitates the use of a shorter length of heating coil, the diameter of the wire used for the coil must be lower for a given resistance and therefore the surface area of wire per unit length of coil is lower; this results in a still further increase in wire temperature.

If hotplates of the sheathed wire type could be so constructed that adjacent turns of the element were actually in contact the energy dissipation per unit surface area and per unit length of coil would be considerably reduced and a life similar to that of the cast iron plate should be obtained. But the surface temperature of such a hotplate would be no higher than that of the cast iron plate and the psychological appeal of the glowing element would be lost. Futhermore, the total mass of such a hotplate would be very little less than that of a cast iron hotplate and it would almost certainly be much more expensive to produce.

In the low voltage open coil hotplate the high surface temperature is permissible for reasons which have already been discussed. One is bound to conclude that, at any rate until such times as new materials become available, the low voltage open coil hotplate is the only form of radiation hotplate with which rapid boiling and long life can both be obtained.

ENCLOSED HOTPLATES WITH WINDINGS SUPPORTED ON LOOSE INSULATORS.

In another class of hotplate which must be briefly considered, the element is not, strictly speaking, embedded, but is insulated by porcelain or similar insulators from a sheet metal or cast iron top. With this construction the energy transmission from the wire to the hotplate top is partly by radiation and partly by conduction and the total thermal resistance between the wire and the vessel is very much higher than it is with either completely embedded or open coil hotplates, consequently to obtain anything approaching a satisfactory life loadings must be very low and fast boiling is therefore out of the question.

APPENDIX.

TESTING.

Both manufacturers who are engaged in the development of hotplates and supply engineers frequently wish to compare the performance of two or more hotplates, and unless great care is taken in the control of test conditions, misleading results may easily be obtained. It is not proposed to discuss the question of tests in detail as very complete recommendations are shortly to be published by the Electrical Research Association. It is felt, however, that some notes concerning points to which it is necessary to pay particular attention in carrying out tests would not be out of place.

The most important properties which one wishes to test are boiling time (efficiency is determined from the results of this test by direct calculation), insulation resistance and life.

Boiling Time.

The difficulty associated with the determination of boiling time is that on account of the very simple nature of the test one is apt to omit the precautions which are necessary to ensure accurate results. It is essential that, in every test, the water should be heated through the same temperature range (85°C is recommended) and that it should be kept well stirred during the test and that the vessel should be covered by means of a well fitting lid. It is frequently difficult to read the thermometer with accuracy as the water reaches boiling point, and much more reliable results are obtained by taking readings of the thermometer at intervals of 1 minute from the commencement of the test and determining the boiling time from the curve obtained by plotting these readings.

When hotplates of different types are to be compared it is often difficult to decide what kind of vessel to use. Table II. gives the boiling times for 3 pints of water for three representative types of hotplates used with a number of different vessels, and it will be seen that in every case there is a very wide variation in the results obtained with the different vessels. The nature of the variation depends on the manner in which the hotplate transmits its heat to the vessel.

In the case of the cast iron hotplate the heat transfer is almost entirely by conduction, either from metal to metal or through a small air film, and the shortest boiling times are obtained with flat bottomed vessels. The boiling time increases with increasing curvature of the vessel bottom, as will be seen by comparing the figures given in Table II. with the curves in fig. 8. The absorption coefficient of the bottom of the vessel, on the other hand, has but little effect, in fact in the case of the flat bottomed aluminium vessel and vessel A blackening the bottom of the vessel has no effect whatever.

In the case of the open coil hotplate the heat transfer is almost entirely by radiation and the heat absorption coefficient of the bottom of the vessel is the predominating factor while curvature is of but

little importance. The shortest boiling time is obtained with the vitreous enamelled vessel since the absorption coefficient of vitreous enamel, of any colour, is practically unity.

The behaviour of the sheathed wire hotplate has already been fully discussed and need not be considered further here.

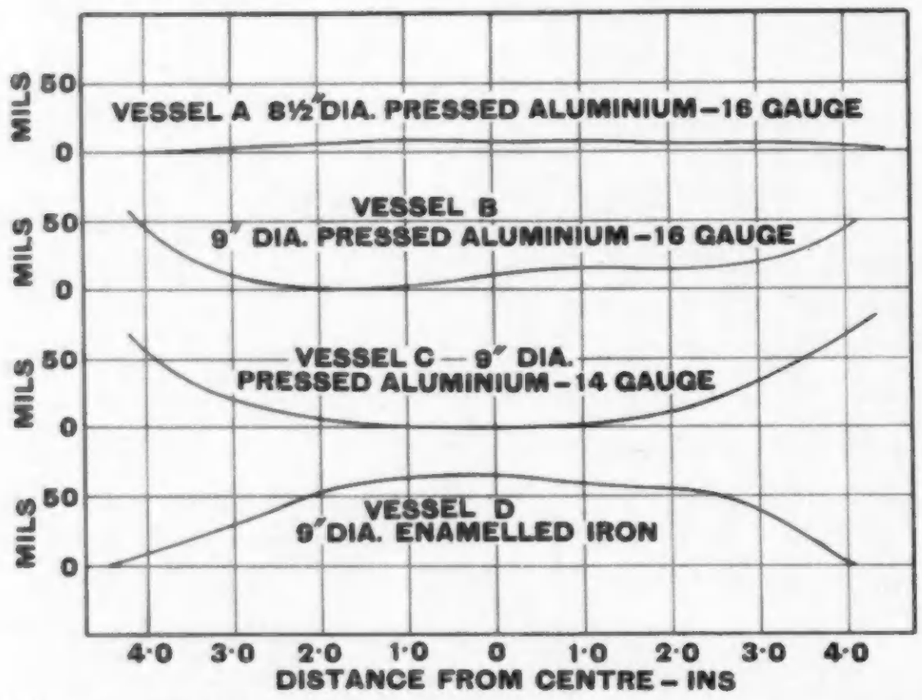

MILS
50
0
VESSEL A 8½" DIA. PRESSED ALUMINIUM – 16 GAUGE
VESSEL B
9" DIA. PRESSED ALUMINIUM – 16 GAUGE
VESSEL C – 9" DIA.
PRESSED ALUMINIUM – 14 GAUGE
VESSEL D
9" DIA. ENAMELLED IRON
4·0 3·0 2·0 1·0 0 1·0 2·0 3·0 4·0
DISTANCE FROM CENTRE – INS

Fig. 8.—Diagram showing the degree of flatness of the bottoms of various vessels.

In every case the best result is obtained with either the flat bottomed aluminium or the vitreous enamelled saucepan, and since the object of the boiling test is the determination of the best boiling time which the user can get using commercially obtainable utensils, it is suggested that the most satisfactory arrangement is to use flat bottomed vessels when testing flat topped hotplates and enamelled iron vessels when testing radiation type hotplates.

Insulation Resistance.

The only reliable method of determining the insulation resistance of a hotplate is to measure the leakage current, while the hotplate is on circuit, between the resistor and such parts of the support as would normally be earthed. Full details will be found in the publication of the E.R.A. to which reference has already been made.

Life.

The most important factor concerning a hotplate is its life, and it is very unfortunate that there is no quick means by which a practical determination of this quantity can be made. Theoretical considerations enable one to make a rough estimate of the comparative lives to be expected from hotplates of different types, but a good general design may easily be spoiled by a mistake in some essential detail, by the use of unsuitable materials, or by slackness in manufacture. Consequently a life test is really called for.

The failure of nickel chromium resistors, at the temperatures at which they operate in hotplates, is due mainly to the local flaking of the protective oxide coating which may occur owing to the difference between the coefficients of expansion of the metal and the oxide, when the hotplate is switched off and the wire cools down. Each time the oxide is removed a fresh metal surface is exposed which itself becomes oxidised, thus forming a new protective layer, the next time the wire is heated. During the course of a large number of cycles of heating and cooling, the oxide may flake off from the same section of the wire on a number of occasions and each time the diameter of the metal core will be reduced. Its temperature rises in consequence and a "hot spot" is formed which eventually reaches so high a temperature that failure occurs. Now if the wire were never allowed to cool, flaking of the oxide would not occur, failure could only take place as the result of oxide penetration, and consequently the

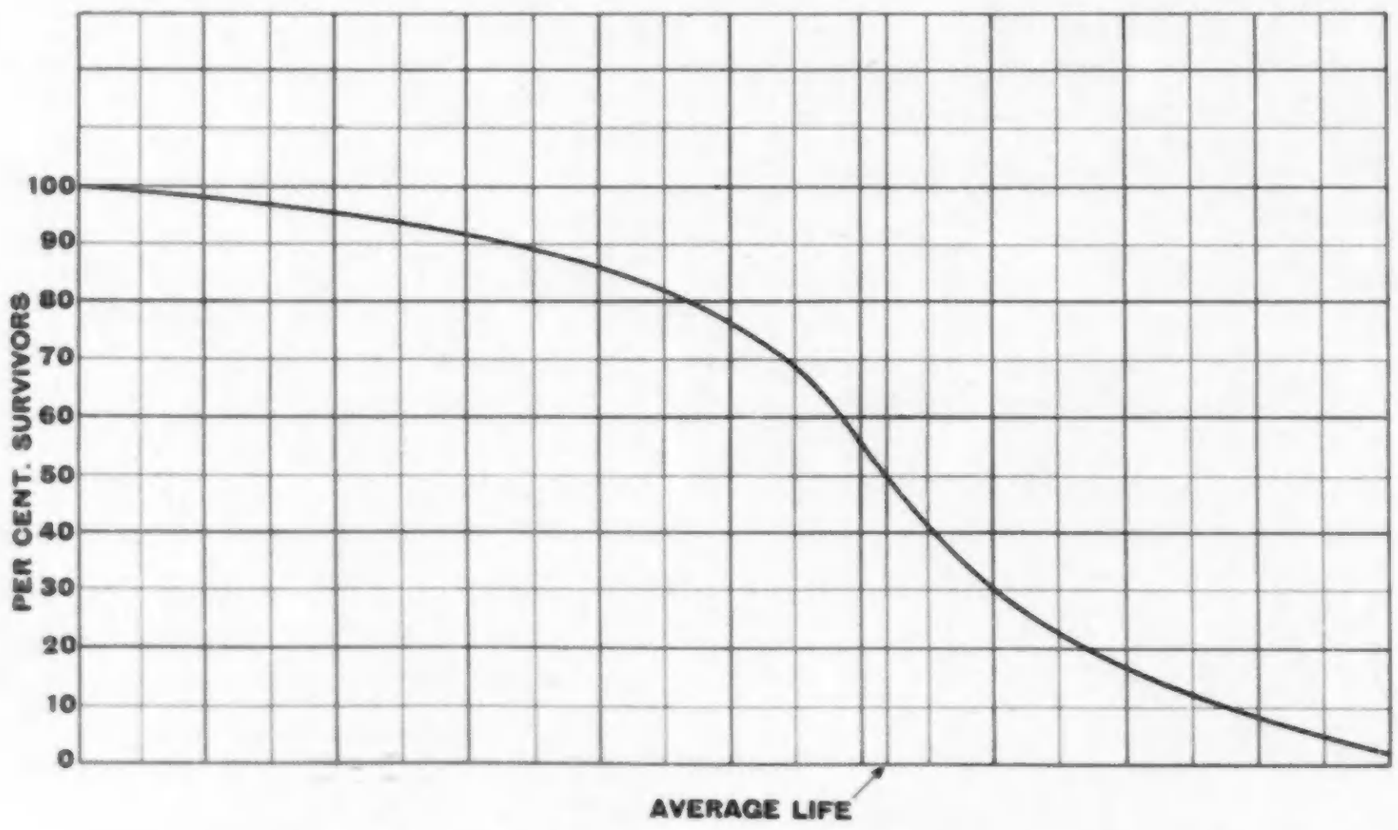


Fig. 9.—Survivor curve of 35 8-inch diameter Magnet hotplates.

life of the wire would be very much longer. The ratio of the lives in the two cases may easily be as high as 5 to 1. For this reason it is essential that a hotplate life test should be intermittent. The period on circuit should be sufficient to ensure that the hotplate is maintained at its maximum temperature for a considerable proportion of the total time on circuit, and the time off circuit should be long enough to enable the hotplate to cool down to about 100°C. In general, 1 hour on and ½ hour off will be suitable intervals, but increasing the periods to 2 hours and 1 hour respectively ensures that the test will be applicable to any hotplate now on the market or likely to be developed.

No vessels should be on the hotplates during the life test but it is very desirable that measurements of loading, boiling time, insulation resistance and surface flatness should be made periodically as the life test proceeds. A hotplate must be written off as a failure either when the resistor burns out or when the hotplate becomes fractured or deformed in such a way as to render it unsuitable for further use.

The relation between the results of the life test and the life to be expected under conditions of domestic use is not easily determined, and in any case will depend to a considerable extent on the actual conditions of use. A flat topped hotplate, for example, which is invariably used with a flat bottomed vessel should have a practically indefinite life, whereas the life of the same hotplate used with badly distorted vessels would be approximately equal to the life obtained in the life test. All one can say at present is that in the case of flat topped, embedded hotplates, a life of about 3000 hours under life test conditions corresponds to a very satisfactory life on the market.

A further point to be borne in mind in connection with life tests is that there will inevitably be a considerable variation between the lives of individual hotplates and for this reason tests on 1 or 2 hotplates are of very little value. The extent of the spread which is to be expected can be seen from the survivor curve in fig. 9 which is based on the results of tests on 35 hotplates. If a number of consecutive periods are taken, starting from the commencement of the test, each period being equal to $\frac{1}{5}$th of the average life, the percentage of failures in each period is shown by the survivor curve to be as follows:

1st period	.. ..	2.5 per cent.
2nd period	.. ..	3.5 per cent.
3rd „	.. ..	6.5 „
4th „	.. ..	11.5 „
5th „	.. ..	26 „
6th „	.. ..	29 „
7th „	.. ..	12 „
8th and subsequent periods		9 „
	Total	100 „

Fig. 10.—General view of hotplate life testing department at the Wembley Research Laboratories of the G.E.C.

In practice this means that if the average life in the hands of the consumer happened to be 5 years, 55 per cent of the hotplates would be expected to fail during the 5th and 6th years, 24 per cent would fail during the first 4 years and 21 per cent during the 7th, 8th and subsequent years.

It is clear that if only one or two plates are tested the results may be very misleading. The E.R.A. has selected 12 as the smallest number from which a reliable average result can be expected. It is appreciated that the life testing of hotplates is an expensive procedure. For example, a 2 kW hotplate tested intermittently as described above consumes 32 units per day, or 224 units per week, and as a satisfactory life necessitates a test of 27 weeks duration, the energy alone for 12 hotplates will cost about £150 representing a consumption of 72,500 units at ½d. per unit. The results of life tests on two or three hotplates are of little value and are thus relatively expensive whereas the more reliable indication of the average life obtained by testing a larger number is well worth the added expenditure.

The Electrification of Bansberia Jute Mill No. 2, Calcutta.

By P. S. JACKSON, M.I.E.E., M.I.E. (Ind).
Chief Engineer of The General Electric Co. (India) Ltd.

INTRODUCTION.

THE jute industry of Bengal, where the hot and moist climate is ideal for the growth of the jute plant, is in some ways one of the most interesting in the world, for the many attempts to grow jute elsewhere have never been attended with real success.

Next to Calcutta, Dundee in Scotland is the most important centre for jute manufacture and while it is interesting to note that Acland, the founder of the jute industry was an Englishman, it is not surprising that some hundreds of Scotsmen from Dundee are at present engaged in approximately 90 jute mills in and around Calcutta.

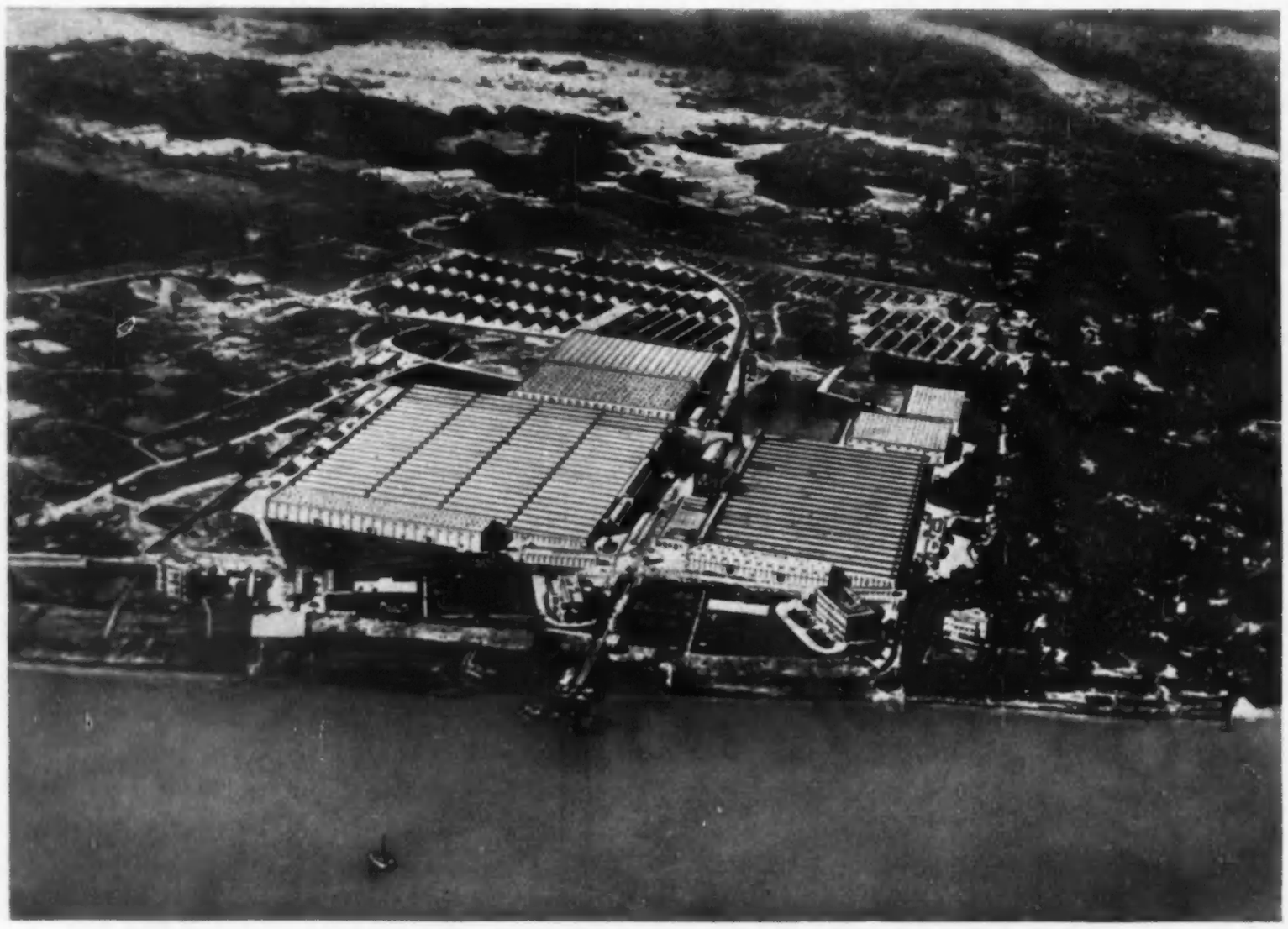


Fig. 1.—Aerial view of Bansberia Jute Mills Nos. 1 and 2.

The first jute mill in Bengal was started in the year 1855 at Rishra near Calcutta, the original output of manufactured jute being 8 tons per day.

Some idea of the rapidity of the growth of the industry may be gauged from the fact that in 1859 there were only 192 looms in operation in Bengal jute mills, whereas in 1931 there were over 58,000, producing about 4,000 tons of manufactured jute per day and giving employment to 350,000 operatives. It might be noted that the jute industry is responsible for 25 per cent of the total export of merchandise from the whole of India.

Prior to 1910 the jute mills in Calcutta were mostly driven by Corliss steam engines, driving by means of ropes on to the main and subsidiary shafting of the mills. In 1910, however, electric driving was introduced by one of the large mills which built its own central electric power house and adopted the electric drive on the group system for the whole mill. Since then, a large number of mills have changed over to the electric drive, obtaining power either from their own independent turbo-alternator power house, or from the public electric supply mains, while a new mill of the Ganges

Manufacturing Co., Ltd., at Bansberia, has been equipped electrically throughout. As this mill is one of the largest in the world and represents the most modern practice in jute manufacture, it is proposed in this article to describe its layout and the electrical equipment installed.

BANSBERIA MILLS.

The new mill is known as Bansberia Jute Mill No. 2 and is situated close to the old mill (Bansberia Jute Mill No. 1). An aerial view of both mills is shown in fig. 1; the old mill, which is steam driven, being indicated by the boiler house and chimney.

No. 1 mill, which has 504 looms and is driven by a modern steam turbine, was started in July, 1926. It is interesting to note that after 3 years' experience with the steam turbine drive in No. 1 mill, the Directors decided on the all-electric drive for No. 2 mill.

When in 1924 the Company took over possession of the area on which the two mills are situated, it was uninhabited and consisted of a malarious jungle. One of the first problems was to recruit labour and to provide housing accommodation. A total of 1,236 huts were therefore built with a first class drainage system and tube wells were sunk to give a liberal supply of drinking water. A modern septic tank system was also introduced for dealing with all sewage. At the same time a bazaar for the sale of cloth, rice, and the like was established under the Company's control, while as Bansberia is a Hindu district, a mosque had to be erected for the Mohammedan workers. For the workers' amusement a free cinema entertainment is provided once a fortnight.

Since the starting up of No. 2 mill, 1,836 huts have been added making a total of 3,072 huts provided for the accommodation of labour. The lines of huts are well lit with electric light and free medical attention is available. An up-to-date hospital has also been built for cases requiring careful nursing. During the first year in which No. 1 mill was in operation a serious outbreak of malaria occurred, but the preventive measures adopted combined with the good drainage of the district soon enabled the outbreak to be brought under control.

Mention may be made here of the system of working in Calcutta jute mills. In the past the double shift system has been in general use, the mills beginning work at 5 a.m. and finishing at 7 p.m. This arrangement has now been universally replaced by the single shift system whereby the mills work from 6 a.m. till 11 a.m. and from 1 p.m. to 6 p.m. In view of the present trade depression, however, most of the Calcutta jute mills work only 4 days per week.

PARTICULARS OF MILL (No. 2).

The following general information with regard to the mill should be of interest.

Total number of spindles installed	19,668
Total number of looms installed ..	1,000
Normal output of the mill in tons of manufactured material per 10 hour day	68
Approximate power consumption in Board of Trade units per ton of manufactured material .. (*Note*:—This power consumption figure varies considerably; with a large proportion of heavy cloth being manufactured the figure decreases and *vice versa*).	316
Approximate total number of employees when mill is in full work	6,000
Price paid per unit for power	.55 annas (.62 pence).

The comprehensive contract for the whole of the electrical equipment, involving motors, switch and control gear, transformers and cables, was awarded by Messrs. Macneill & Co., Managing Agents of The Ganges Manufacturing Co., Ltd., to The General Electric Co. (India) Ltd., Calcutta Branch, the Consulting Engineer being Mr. J. C. Taylor, M.Inst.C.E., M.I.E.E., who together with Mr. David Miller, Superintendent of Messrs. Macneill's Jute Mills, Calcutta, and Mr. J. Robertson, Manager of the Bansberia Mills, were responsible for the whole of the design and arrangement of the lay-out of the plant.

In addition, all the mill electric lighting work, together with wiring and fittings and telephone installation was carried out by The G.E.C. (India) Ltd. Mr. J. Dryburgh, Electrical Engineer, Bansberia Mills co-operated with the contractors throughout the whole of the installation.

MANUFACTURING PROCESS.

In describing the motor drives in this article, frequent reference is made to shafts in the various departments. A short description of the manufacturing process, therefore, will assist the reader to grasp the layout.

During the process of manufacture the jute passes through seven departments in the mill and factory. These departments are named Batching, Preparing, Spinning, Winding, Beaming, Weaving and Finishing.

The term "mill" is generally applied to the first five of these departments, and "factory" to the Weaving and Finishing departments. The machinery in each department is divided up into what is termed systems and the total number of systems are divided into the different grades of manufacture of hessian cloth and sacking, etc.

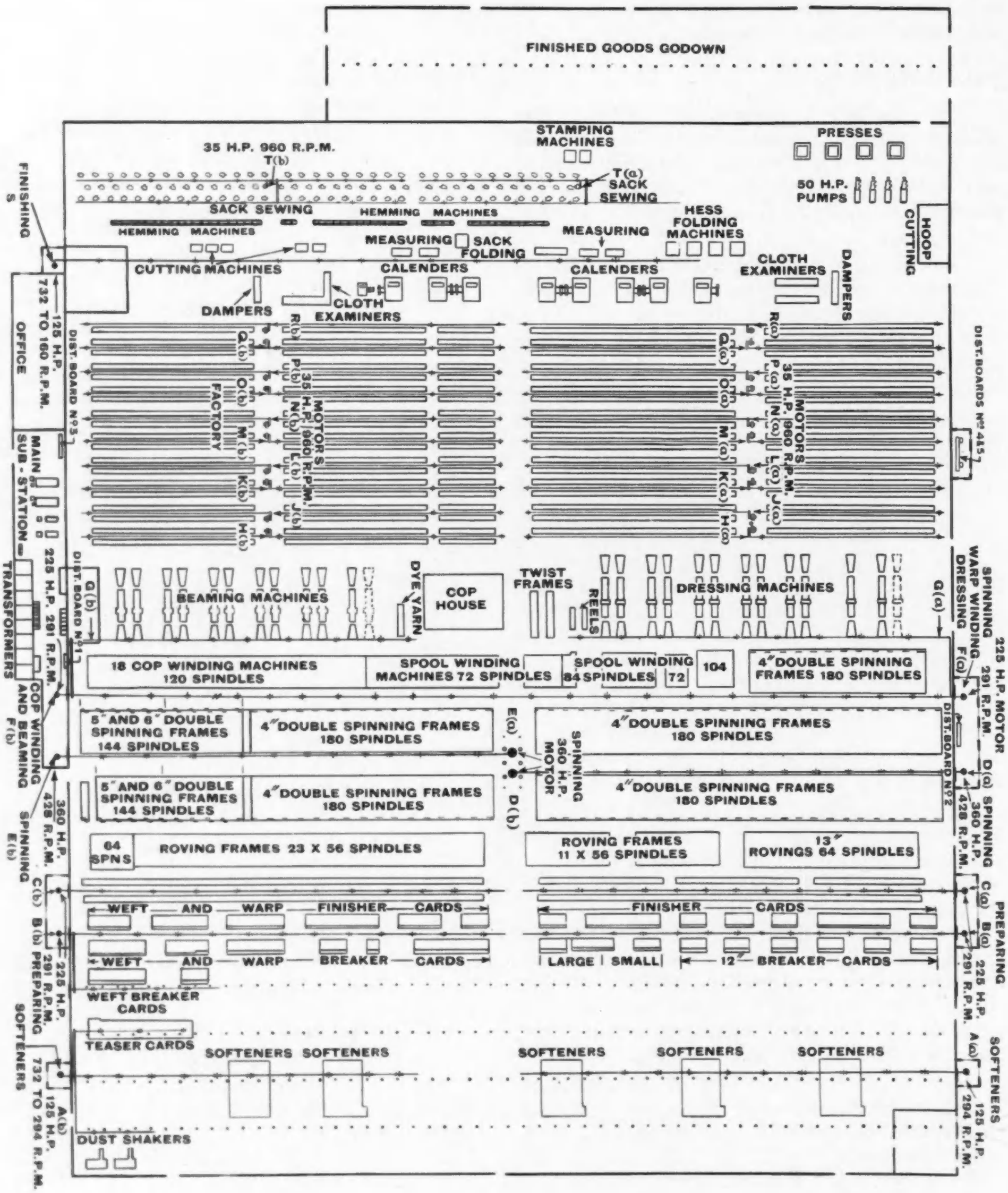


Fig. 2.—Arrangement of machinery, shafting and motors for Bansberia Jute Mill No. 2.

Batching. The raw jute is received at the mill either by rail or cargo boat, from jute balers in Eastern Bengal where most of the jute fibre is grown. For this purpose a railway siding, and a jetty in front of the mill on the Hooghli River, have been provided. When they are required, the bales of jute are brought in to the mill from the jute "godowns," or warehouses, and what is known as a "batch" is formed consisting of a few bales of different "marks" blended together. These are opened and the different qualities selected. As a general rule the stronger jute goes to form warps and the weaker jute to make wefts.

Preparing. After the jute has lain for the necessary time in the Batching Department it is taken to the Preparing Department where the jute is converted from the "streak" into rove yarn for the spinning process. The conversion is effected by the use of five different machines, namely :—

(*a*) Jute breaker card.
(*b*) Jute finisher card.
(*c*) 1st drawing frame.
(*d*) 2nd drawing frame.
(*e*) Roving frame.

During its passage through the breaker and finisher machines just mentioned the jute undergoes what

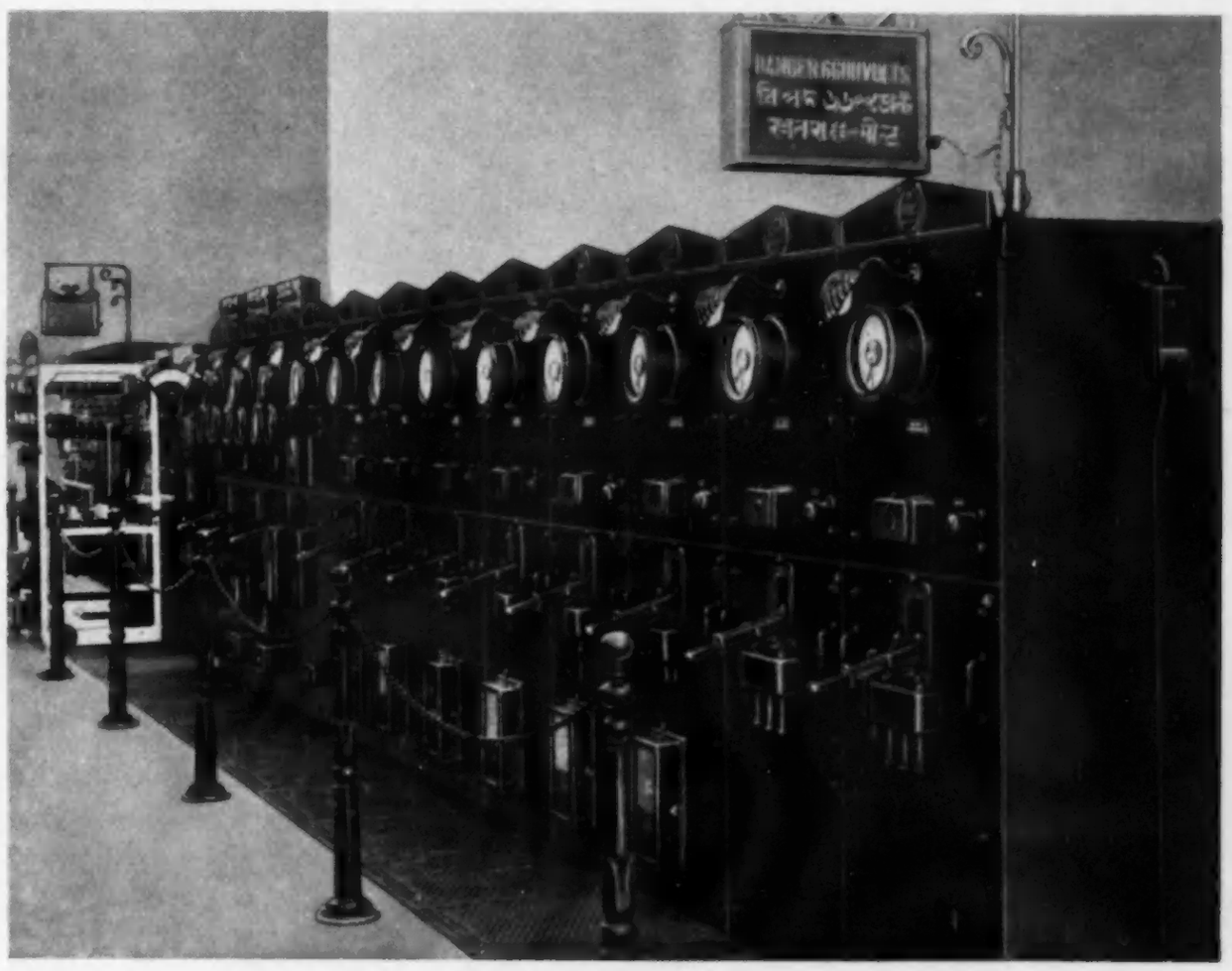


Fig. 3.—Main 6,600 volt, 3 phase, 50 cycle, truck cubicle switchboard.

After selection the jute is fed through softening machines which comprise a series of sixty pairs of right and left hand fluted spiral rollers pressed together by spiral springs. While passing through these rollers a stream of mineral oil, known as "batching" oil,* and water is allowed to run down from overhead pipes on to the fibre. During this operation the jute is softened and damped and is then delivered at the other end of the machine, each "streak" being twisted and laid on a trolley.

General practice is to let the jute lie for at least 24 hours before taking it to the next process so that the oil and water may percolate through the fibre, slackening the root and dust and rendering it fit for the "carding" process which follows. Very much of the success of the working of the material in the other departments depends on the care and attention given to the material in the Batching Department.

* In different mills the application of the batching mixture varies.

is termed the "carding" process. By means of a cylinder and rollers covered with carding pin lagging set at different angles, the jute is combed out into a tow and during the process is "drawn" to a certain extent.

In the drawing frame a number of ends, or "slivers," are put up at the back of the machine and all run into one end at the front, thus helping to equalise any irregularities arising from the previous process. At the same time the jute is drawn out smaller and finer.

In the roving frame one end is put through the frame by itself and, while passing through the frame, is drawn finer still and delivered at the front to the weight required for the yarn. When it is delivered at the front of the roving frame, and as it is laid on its bobbin, a certain amount of "twist" is given to keep it together whilst it is being unwound from the bobbin during the spinning process. As soon as the rove bobbins are filled

at the roving machine they are taken to the Spinning Department.

Spinning. Each spinning frame in the Spinning Department has either 72 or 90 spindles. The "roves" brought from the Preparing Department are placed on racks on top of the spinning frames. During the process the jute is drawn and twisted and wound on to bobbins of various sizes to suit the requirements of the cop and spool winding machines.

Winding. In the Winding Department the spun jute is wound on to spools for the Beaming Department and into cops for the shuttles of the weaving looms.

Beaming. The spools from the winding are mounted on a frame and threads fed over steam heated drums and through a starching process on to large drums called "beams" containing the "warp" material for the looms.

Weaving. From the beaming machine the "Beams" are passed to the looms, and the cops for the loom shuttles are obtained from the Winding Department as previously mentioned. The beams form the "warp," and the cops the "weft" of the cloth. The finished pieces of cloth, 80/100 yards long are called "cuts." The warps and wefts are woven together to form fabric. The weft is dragged from the eye of the shuttle as it is driven across the loom through the warp shed and it is beaten up as the loom "lay" comes forward. The woven "cut" is now taken from the factory and examined for faults as it passes over inspection tables, after which it passes over the damper machine where it is given a slight moistening to help the finishing process through the calenders.

Finishing. The finishing process includes imparting a "finish" to the cloth by calenders and mangling machines which consist of large rollers. The mangles are arranged with reversing motion but the calenders run continuously in one direction. The cloth is pressed by being passed through the rollers. In the case of the rollers of the calenders, the pressure is applied by means of balance weights, while pressure is applied hydraulically to the rollers of the mangles. From these machines the cloth is passed to measuring machines and in turn to inspection tables and lapping machines where the "cuts" of cloth are folded. The folded cloth is then passed to the hydraulic baling presses and placed in bales for export.

Sacking cloth is usually just passed from the looms through measuring machines and on to the cutting and sewing machines. The finished sacks are also put up into bales for export.

ELECTRICAL EQUIPMENT.

In order to appreciate the extent of the electrification it has been considered desirable to schedule the electrical equipment involved. This is set out in the following sections.

A. SWITCHGEAR.

No.	No. of Panels	Type	Voltage	Purpose.
SWITCHBOARDS				
1	12	Truck	6000	Controlling E.H.T. Power Supply.
2	7	Truck	3300	Controlling 3300 volt Power Supply from the three 1750 kVA transformers.
3	6	Flat Back	400	Controlling 400 volt Power from the three 625 kVA transformers.
4	9	Flat Back	230	Controlling Direct Current Supply from Motor Generators for lighting, ventilating, cranes, etc.
DISTRIBUTION BOARDS.				
1	8	Ironclad Industrial Draw-out	3300	Controlling 3300 volt supply to main mill motors. Located in main sub-station.
2	5	ditto	3300	Ditto but controlling main mill motors at South end of mill. Located in sub-station at south end of mill.
3	11	ditto	400	Controlling 400 volt supply to weaving shaft, etc., motors.
4	11	ditto	400	ditto.
5	4	ditto	400	Controlling 400 volt supply to pump motors.

B. MOTORS AND CONTROL GEAR.

Driving.	No. of Motors	Type of Motors.	B.H.P.	Speed.	Voltage.	Method of drive.	Type of Starter.
Main Spinning Shafts.	4	Synchronous Induction.	360	428	3300	Directly coupled.	Liquid.
Preparing and Winding Shafts.	6	Slipring.	225	291	3300	Directly coupled.	Liquid.
Batching and Finishing Shafts.	3	Slipring.	125	732	3300	Chain.	Liquid.
Hydraulic Pumps.	4	Slipring.	50	730	400	Spur Gearing.	Oil-immersed Rotor.
Weaving Shafts.	20	High torque sq. cge.	35	960	400	Chain.	Auto Transformer.
Sack Sewing, Hemming and Stamping Shafts.	2	Ditto.	35	960	400	Chain.	Ditto.

Total number of mill motors installed .. .. 39.
Total mill B.H.P. installed .. .. .. 4,135.

C. MOTOR-GENERATOR SETS.

GENERATORS.				MOTORS.			
No. of sets.	Output in kW.	Volts.	Speed.	Type.	B.H.P.	Voltage.	Type of Starter.
2	250	230	1000	Syn. Induction.	355	3300	Liquid.
2	80	230	965	Slipring.	125	3300	Liquid.

D. TRANSFORMERS.

Oil immersed self cooled core type indoor pattern power transformers, complete with oil expansion vessels, calcium chloride breathers and "off-load" tap changing switches.

No. of Transformers.	Purpose.	Output in kVA.	Ratio.	Connection.
3	Supplying power to H.T. motors.	1750	6000/3300	Delta/Star.
3	Supplying power to L.T. motors.	625	6000/400	Delta/Star.
2	Supplying power to 80 kW M.G. sets.	125	6000/3300	Delta/Star.

E. WIRING AND LIGHTING INSTALLATION.

25 miles Pirelli-General wire, V.I.R. Class 101, 600 megohm "Association" grade wires and cables.

Over 1300 " Geco " dispersive reflectors for 100, 200, 300 watt Osram gasfilled lamps.

F. TELEPHONE INSTALLATION.

15-line, G.E.C. wall mounting telephone switchboard, visual signal pattern, operated from central storage battery.

POWER SUPPLY.

Power is purchased from The Gourepore Electric Power Co. Ltd., whose power station is situated at Naihati, some 5½ miles away on the opposite bank of the Hooghli River.

Three 3-core 6600 volt underground power cables convey the power from the power house across the Jubilee Railway Bridge over the Hooghli to the mill substation.

MAIN SUB-STATION, SWITCHBOARDS AND TRANSFORMERS.

On arrival at the substation the main cables terminate at three 6000 3-phase 50 cycle truck type cubicles which form part of the main E.H.T. truck type switchboard, illustrated in fig. 3. It will be noted that the three incoming panels are at the extreme left-hand end of the board and, to the left of them, will be seen a spare panel, the truck for which has been withdrawn for examination.

This main switchboard is also fitted with cubicles for controlling the supply to the three main 1750 kVA 3 phase transformers which step down the voltage from 6000 to 3300 volts.

From the main E.H.T. board power is led direct to the three 1750 kVA transformers. Each transformer is housed in a separate masonry cubicle provided with an expanded metal door giving ample ventilation. Thence the power is conveyed to the main 3300 volt truck type board. Fig. 4 shews all the eight transformers installed in their respective cubicles.

The illustration of the 6000 volt board in the substation, fig. 3, also shows all the eight transformer control panels while fig. 5 shows the plant installed in the main substation, the 6000 volt board being on the right-hand side with the 3300 volt board and direct current board opposite. From the 3300 volt board power is taken to the various main mill motors, which drive the shafts indicated in fig. 2, a schedule of which is given in the following table.

Fig. 4.—General view of the eight transformer cubicles.

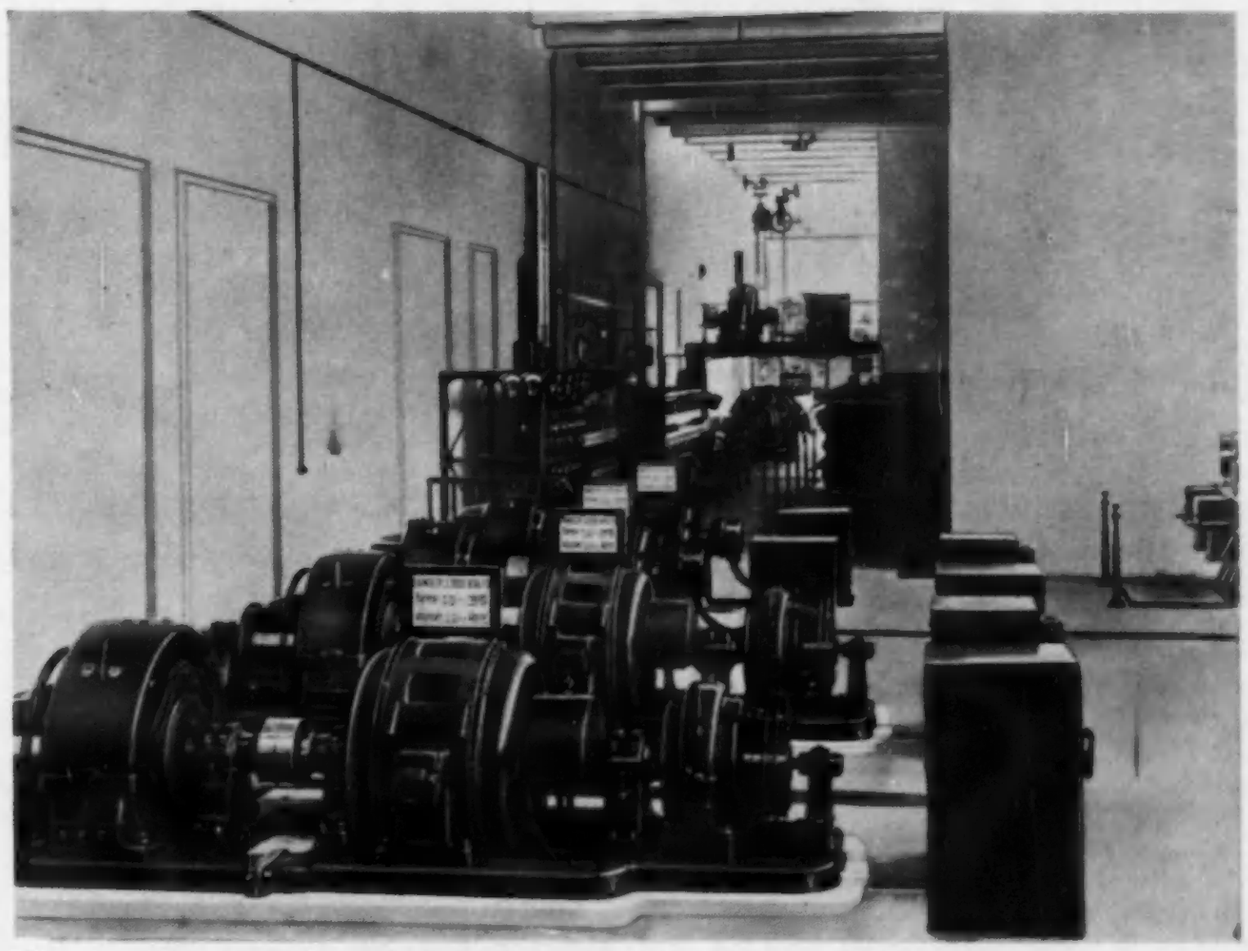


Fig. 5.—General view of the substation showing two 250 kW synchronous and two 80 kW slipring motor generators; also main switchgear and in the distance one of the main mill motors.

Shaft	A	(a)	for Softeners.
,,	A	(b)	for Softeners and Rovings, Finisher Cards, Breaker Cards, Drawing Frames.
,,	B	(a)	for Finisher Cards and Breaker Cards.
,,	B	(b)	for Finisher Cards and Breaker Cards.
,,	C	(a)	for Two Headed push-bar Drawings and Roving Frames.
,,	C	(b)	for Ditto.
,,	D	(a)	for Double Spinning Frames.
,,	D	(b)	for Ditto.
,,	E	(a)	for Ditto.
,,	E	(b)	for Ditto.
,,	F	(a)	for Spinning and Spool Winding Machines.
,,	F	(b)	for Spinning and Cop Winding Machines.
,,	G	(a)	for Dressing Machines and Twist Frames.
,,	G	(b)	for Beaming Machines and Dye Yarn.

Shaft H (a) for Looms.
,, H (b) for Ditto.
,, J (a) for Ditto.
,, J (b) for Ditto.
,, K (a) for Ditto.
,, K (b) for Ditto.
,, L (a) for Ditto.
,, L (b) for Ditto.
,, M (a) for Ditto.
,, M (b) for Ditto.

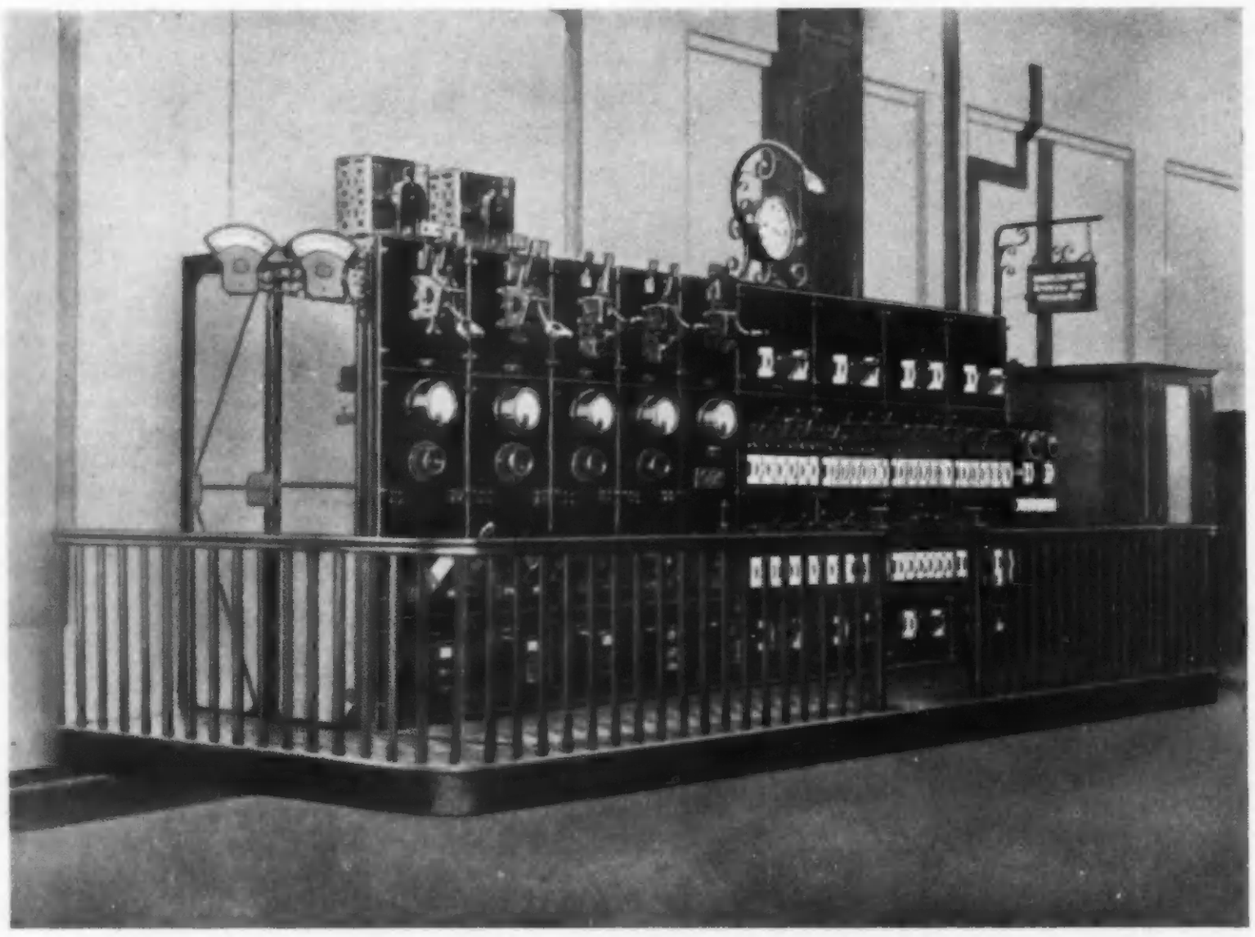


Fig. 6.—Main low tension direct current switchboard in main substation, controlling the whole of the lighting and auxiliary power to the mill.

Shaft N (a) for Looms.
,, N (b) for Ditto.
,, O (a) for Ditto.
,, O (b) for Ditto.
,, P (a) for Ditto.
,, P (b) for Ditto.
,, Q (a) for Ditto.
,, Q (b) for Ditto.
,, R (a) for Ditto.
,, R (b) for Ditto.
,, S for Dampers, Calenders, Cutting Machines and Measuring Machines.
,, T for Hemming Machines and Sack-sewing Machines.
,, U for Sack-sewing Machines and Stamping Machines.

Three of the panels of the 6,000 volt board control the three 625 kVA transformers which step down the voltage from 6,000 volts to 400 volts for the purpose of supplying power to 50 b.h.p. and 35 b.h.p. motors which are referred to in a subsequent paragraph.

In emergency, these transformers can also be used for supplying electric light to the whole mill and during the cool season at such times as direct current power for operating the electric cranes and ventilating fans is not needed. The neutral point of each transformer is connected to the neutral bar on the 400 volt switchboard for this purpose.

D.C. SUPPLY.

The standard practice in the Calcutta Jute Mills is to use direct current for lighting and operating ceiling, desk and other types of ventilating fans, both in the mill offices, residential quarters, etc., also for operating the various electric cranes which are in use in the warehouses or "godowns." For this purpose two 250 kW motor generator sets have been installed; these are shown in fig. 5.

For use during week-ends and at other times when the mill is closed down, two 80 kW motor generator sets have been supplied complete with the necessary transformers for stepping down from 6000 to 3300 volts.

D.C. MAIN SWITCHBOARD.

Fig. 6 shows the main direct current switchboard controlling the whole of the lighting and auxiliary power to the mill. In this connection it is interesting to note that one of the panels of this switchboard connects to No. 1 mill so that when the auxiliary steam direct current generating sets in that mill are shut down, electric power is available from No. 2 mill. Similarly should there be a failure of the supply of power to No. 2 mill, direct current is available through this switchboard for lighting, etc., from the auxiliary steam power plant at No. 1 mill.

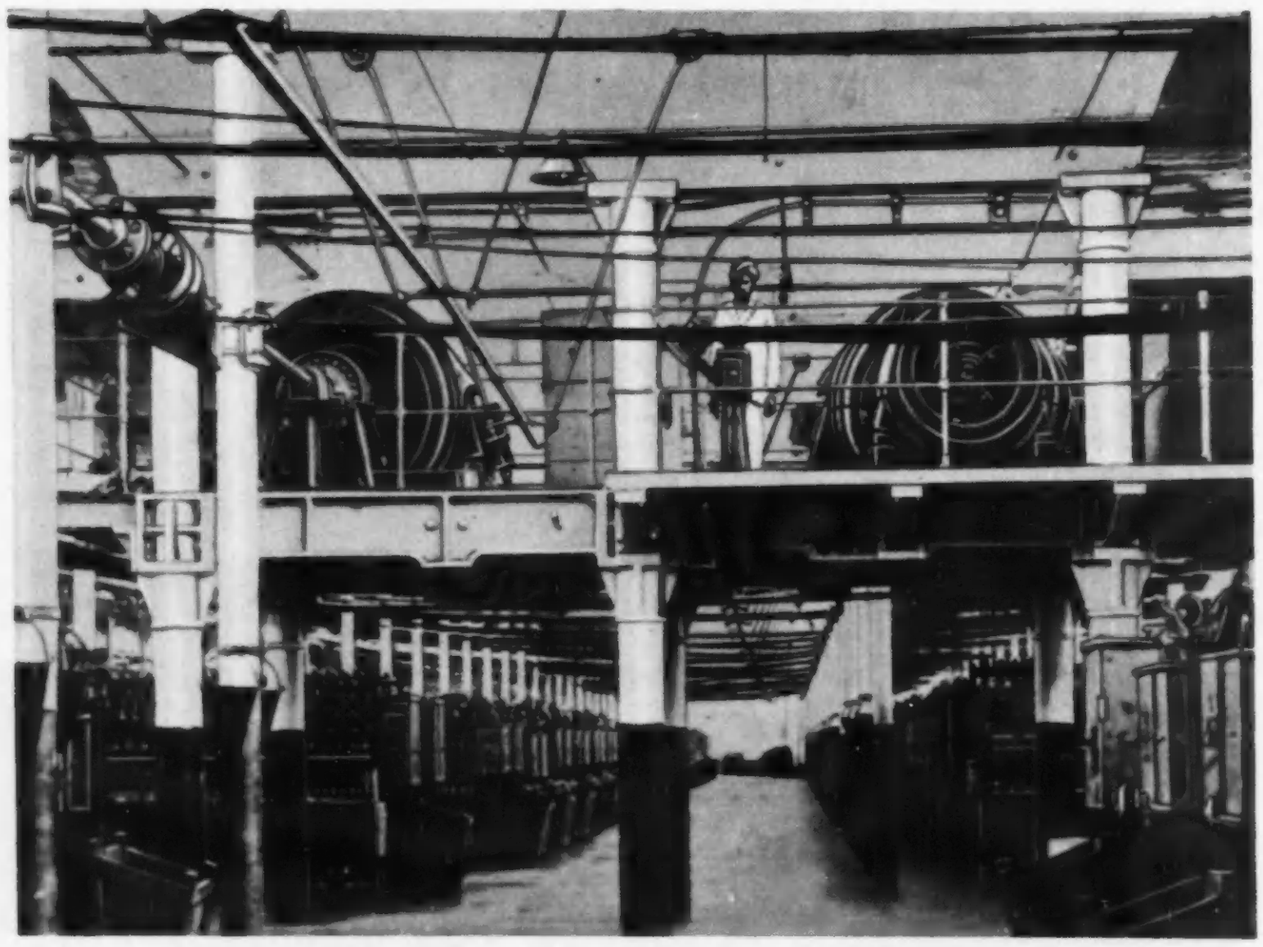


Fig. 7.—Two 360 h.p., 3,300 volt, 3 phase, 50 cycle, 428 r.p.m. synchronous induction motors direct coupled to main spinning shafts E (a) and D (b) (see fig. 2). Note how the elevated platforms enable a clear passage way to be obtained down the centre of the mill.

ARRANGEMENT OF MOTORS AND DRIVES.

All the large main motors in the mill, with three exceptions only, are directly connected to their respective line shafts and operate at 3300 volts, 3 phase, 50 cycles. The loom and sack sewing shafts are, however, driven by 35 b.h.p. high torque squirrel cage motors through enclosed silent chains and these motors, together with the four 50 b.h.p. slipring motors driving the hydraulic press pumps, operate at 400 volts.

The four 360 b.h.p. motors which drive the four main spinning shafts are of the synchronous induction type. They are capable of providing all the wattless kVA required for supplying the magnetising current of all the motors in the mill, and, therefore, the power factor of the whole mill load can be kept at approximately unity under any conditions of working.

As will be seen from the plan of the mill (fig. 2) there is an auxiliary substation at the south end of the mill and this substation contains distribution board No. 2 from which power is distributed to the 3,300 volt motors on that side of the mill. This substation also contains one 360 b.h.p. motor driving the spinning shaft D (*a*) and one 225 b.h.p. motor driving spinning and spool winding machines, etc.

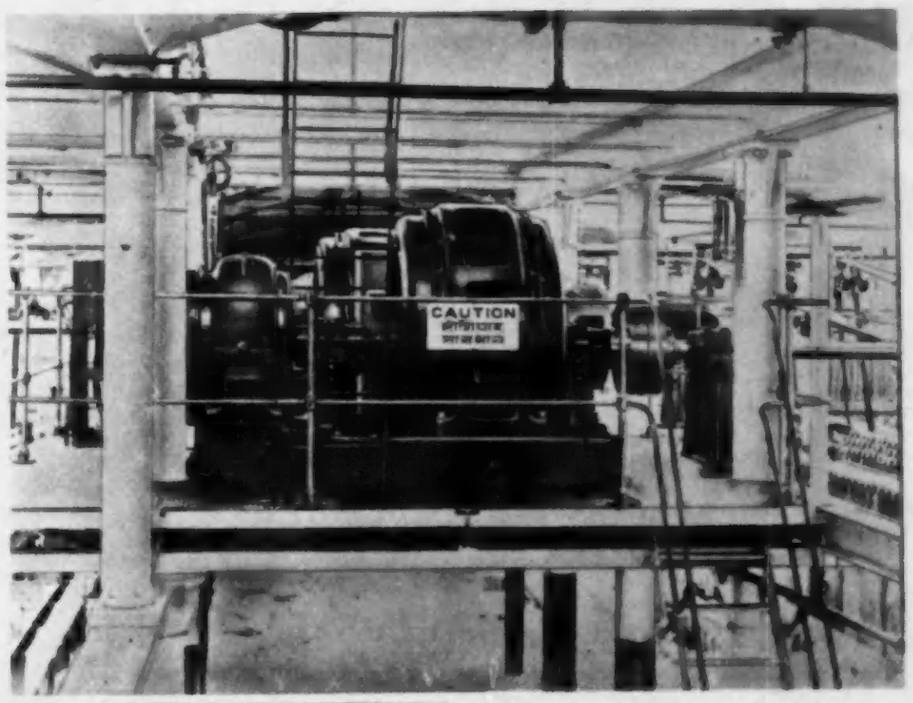


Fig. 8 (above).—Another view of the motors shown in fig. 7.

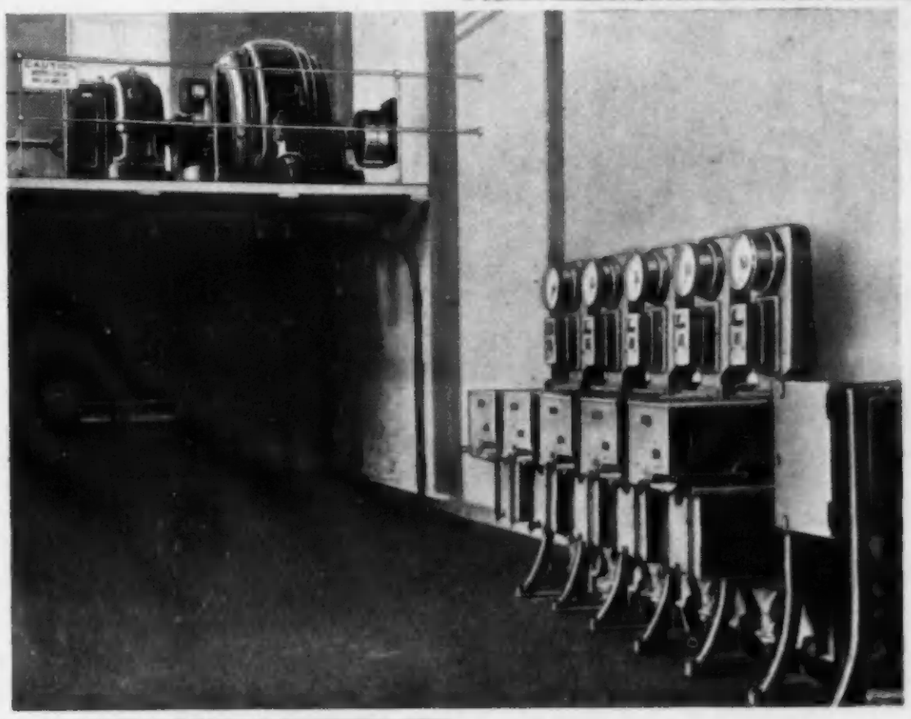


Fig. 9 (left).—360 h.p., 3,300 volt, 3 phase, 50 cycle, 428 r.p.m. synchronous induction motor direct coupled to main spinning shaft D(a).

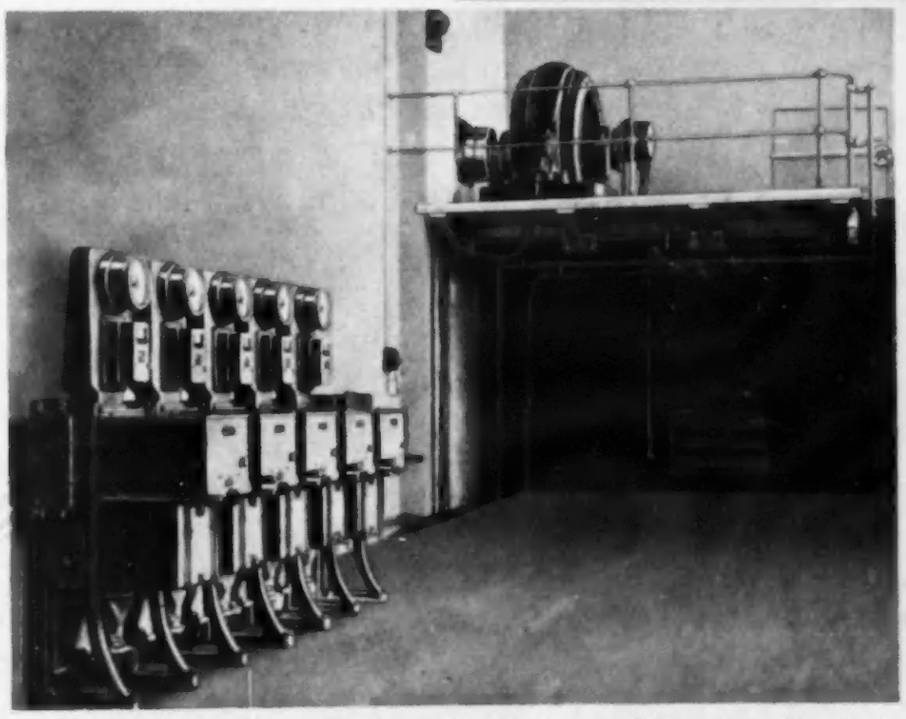


Fig. 10.—225 h.p., 3,300 volt, 3 phase, 50 cycle slipring motor direct coupled to shaft F(a) driving spinning frames and spool machines.

The three exceptions to the statement that all the main 3300 volt motors are direct coupled to their respective shafts, are the three 125 b.h.p. motors connected respectively to shafts A (*a*) and A (*b*) driving the jute softeners and to shaft S driving the finishing machines. Under the heading "finishing" machines may be grouped the damping, calendering, cutting and measuring machines. These motors run at 735 r.p.m. and are fitted with silent chain reduction gears giving 294 r.p.m. on the mill shafting.

It will be noticed that with the exception of the two 360 b.h.p. motors driving shafts E (*a*) and D (*b*), all the main motors are installed in motor houses outside the mill where they are kept perfectly free from dust and "fluff" which is practically unavoidable in the atmosphere of a jute mill. The two 360 b.h.p. motors installed inside the mill are mounted upon motor platforms and, if necessary, the platforms may be enclosed to prevent the entry of dust or "fluff."

At the time of designing the electrical layout of the mill, the question arose as to whether it would not be preferable to install two 720 b.h.p. motors for driving the two main spinning shafts instead of dividing these two shafts into four and installing four 360 b.h.p. motors.

The advantage to be gained by the former proposal was that there would be no 3300 volt main motors inside the mill and that a clear passage would be left right along the centre path of the mill. It was eventually decided, however, to split the drive amongst four motors, and fig. 7 shows that the clear passageway down the centre of the mill has been retained by mounting the two 360 b.h.p. motors on an elevated platform. By this means, the use of much lighter motors has been made possible, and it is only necessary to have one spare

360 b.h.p. motor of comparatively light weight instead of the heavier spare motor of 720 b.h.p. which would have been necessary. A saving has also been effected in the cost of shafting, bearings, etc., as the maximum horse power to be transmitted in any part of the spinning shafts is now only 360 b.h.p. Fig. 8 shows another view of the two main spinning motors in the centre of the mill. The main spinning motor driving shaft D (*a*) is illustrated in fig. 9. This figure also shows the No. 2 distribution board for the five high tension motors situated on the south side of the mill. This distribution board consists of five industrial drawout type oil switches complete with indicating wattmeters and integrating watt-hour meters, and in this connection it is interesting to note that special care has been taken throughout the mill to provide each motor with its own separate watthour meter, so that accurate records can be kept of the power required to drive each section of the mill.

Fig. 10 shows the 225 b.h.p. induction motor connected to shaft F (*a*) driving spinning frames and spool winding machines. It also gives another view of the No. 2 distribution board referred to above and shows the potential transformer pillar on the extreme right of the illustration.

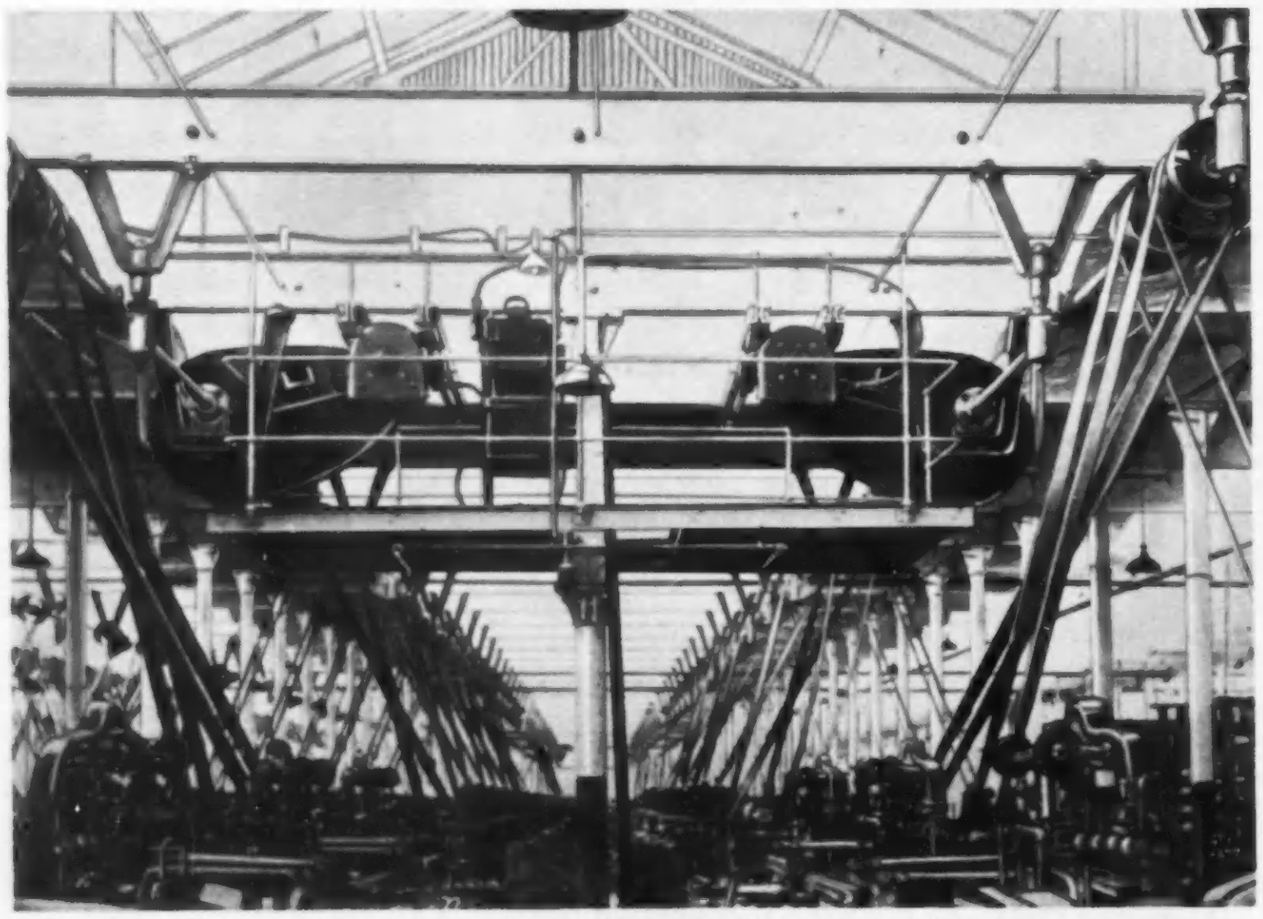


Fig. 11.—35 h.p., 400 volt, 3 phase, 50 cycle, 960 r.p.m. high torque squirrel cage, drip proof induction motors driving looms shafts H. to R.

A 225 b.h.p. slipring induction motor is connected to shaft F (*b*) and drives the spinning and cop winding machines. Underneath the platform on which this motor is installed are two spare motors of 360 and 225 b.h.p. respectively. These are all shown in fig. 5.

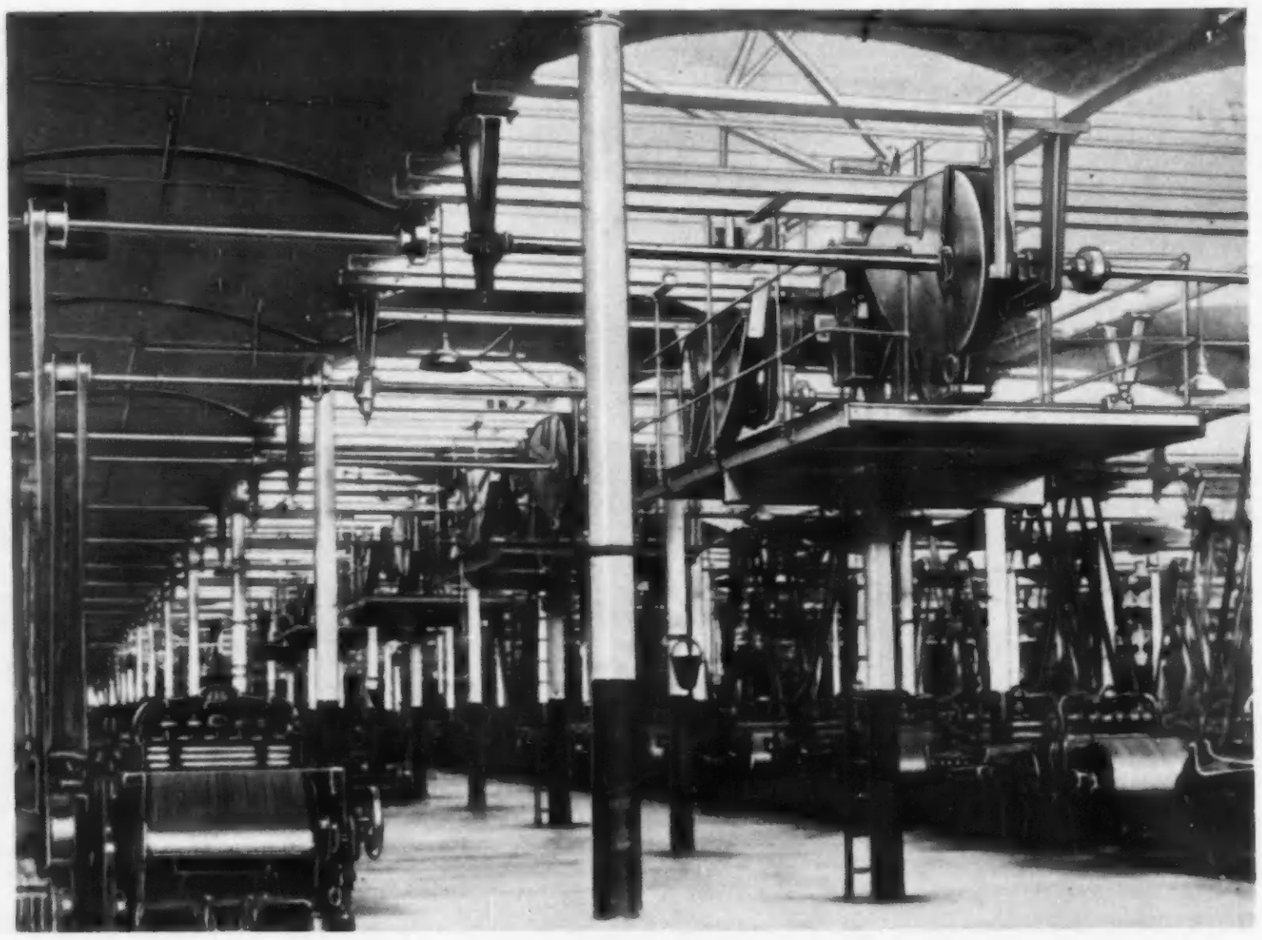


Fig. 12.—General view of loom shafts showing 35 h.p. high torque squirrel cage motors, chain drives and platforms.

The arrangements of the drive for the looms are shown in figs. 11 and 12. Twenty 35 b.h.p. 400 volt 960 r.p.m. high torque squirrel cage motors with auto-transformer starters are used for driving the loom shafts which run at 160 r.p.m. The motors are inverted and the method of fixing them to cross girders is shown in the illustrations. It is interesting to note that several of the loom shafts have been fitted with roller bearings and in actual practice it is found that considerably less power is consumed by these shafts than by similar shafts in the mill which are fitted with oil ring journal bearings of the latest type.

Fig. 13 shows the four 50 b.h.p. 400 volt 720 r.p.m. drip-proof slipring induction motors which are connected to the four hydraulic press pumps through spur gearing.

It should be noted that although there are 39 motors in the mill, there are only 5 different sizes, thus minimising the number of spares necessary.

DISTRIBUTION BOARDS.

No. 3 low tension industrial type ironclad distribution board (fig. 14) fitted with drawout

pattern oil switches, indicating wattmeters and integrating watthour meters, is erected at the left hand end of the main substation (see fig. 2). Each of these switches controls one 35 b.h.p. loom motor.

Nos. 4 and 5 distribution boards are situated on the south side of the mill. These boards control respectively the loom motors on the south side of the mill and the four hydraulic press pumps.

ARRANGEMENT OF CABLES.

A reference to fig. 1 will show that in accordance with standard jute mill practice in India, the mill is of the single storey type and it was therefore found convenient to run the whole of the power lighting and phone cables over the roof of the mill. The cables are run in brickwork ducts provided with reinforced concrete covers, a system which has been found to be thoroughly satisfactory even with a sun temperature approaching 160°F during the hot season. All the power cables are of the 3-core paper insulated, lead covered, double wire armoured type.

TELEPHONE INSTALLATION.

An interesting item of the electrical equipment is the telephone installation. The switchboard has a capacity of 15 lines and is of the wall mounting, visual signal pattern, operated from a central storage battery.

The board has been installed in the substation close to the various motor generator sets, making operating conditions extremely difficult. To overcome this a sound-proof cabinet has been provided in which the switchboard is installed, and operating can thus be carried on in comfort. A special loud ringing bell is mounted on the outside of the cabinet and should the operator leave his sound-proof cabinet he switches this bell into circuit in order to obtain an audible warning when a call is originated.

Of the 15 telephones installed, three had to be installed in particularly noisy situations in the mill. They had to be fitted only a few feet away from a number of spinning frames, the noise from which is so intense that ordinary telephones were quite useless. The problem was successfully overcome by the provision of three special hand-combination telephones, the transmitters being designed to operate by direct contact with the speaker's throat. For this purpose the hand-combination instruments are shorter than the usual type and have a small transmitter without any mouthpiece.

This transmitter is held against the throat and speech is transmitted by direct contact instead of through the usual medium of the air.

In this way extraneous noises, such as those from machines in operation, are not picked up by the telephone transmitter and normal speech can be carried on without interference.

LIGHTING.

In designing a lighting scheme for any Indian jute mill there are two limiting factors to be considered. First, the total lighting load must not exceed a given maximum, and secondly, the foot-candle intensity must not be high.

It must be appreciated that India has not received the same education in better lighting as has Europe or America. Illuminating Engineering has only been known in India during the last few years, and until 5 years ago there was not a single example of properly designed lighting to be seen anywhere in the large industrial district in and surrounding Calcutta. Therefore, to try and impose all at once the standards of illumination now considered essential in Europe would be unwise and useless.

To those in the West therefore, the foot-candle intensities given below will appear inadequate, but to users in India they are invariably considered very good and perhaps a little too high.

In common with all the other jute mills in Bengal, Bansberia is one large single storey building.

The bulk of the machinery is comparatively small and the roof is supported on iron columns which,

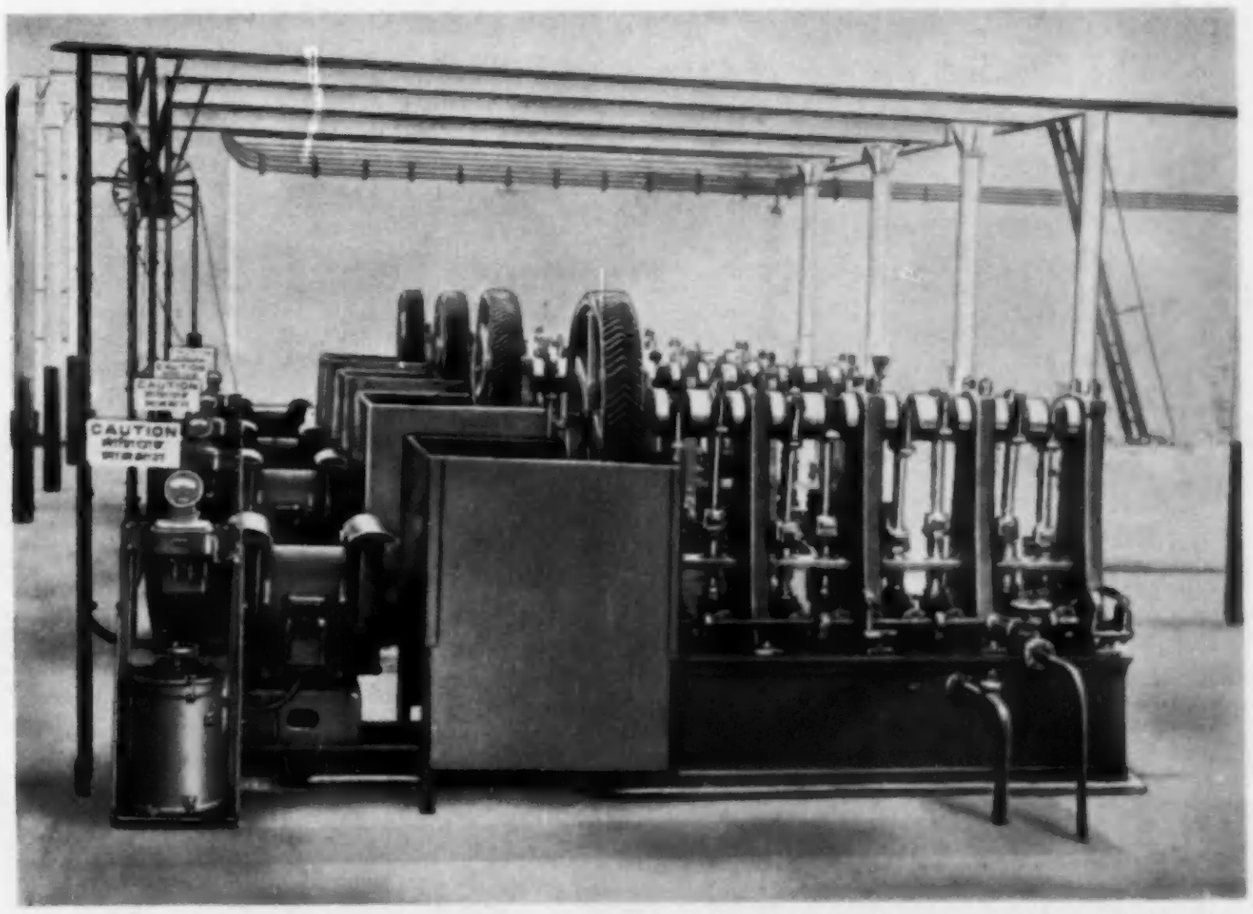


Fig. 13.—Four hydraulic press pumps each driven by a 50 h.p., 400 volt drip proof slipring induction motor, 720 r.p.m., with oil immersed rotor starting panel and interlocked stator control switch.

following standard practice, are spaced 22 ft. by 11 ft. apart. Floor to ceiling height is 14 ft.

Nowhere in a jute mill is the working fine or accurate. The most important section of the mill is the factory where the looms are located. Moderately good lighting is required here to enable the operator to observe broken threads.

In general, a system of general lighting is suitable. The carding machines, which are about 11 feet high, close together and have heavy belting, require local lighting, as also do the sewing and hemming machines in the finishing department. The beaming machines require partly local and partly general lighting.

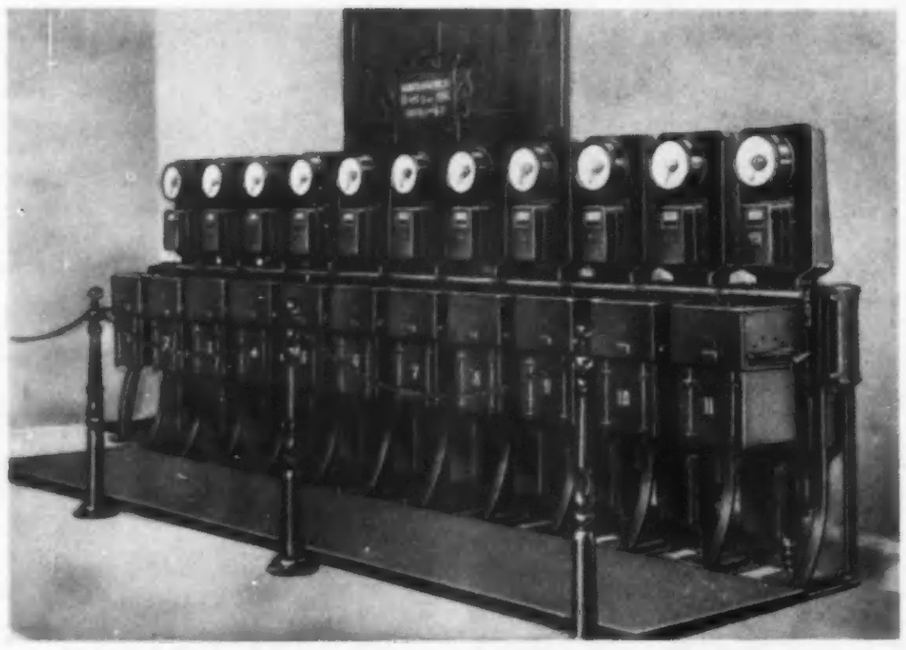


Fig. 14.—400 volt 3 phase 50 cycle industrial ironclad distribution board, each unit controlling a 35 h.p. loom motor.

The lighting system installed in the mill comprises 100, 200 and 300 watt lamps with dispersive type reflectors, and 40 watt lamps with extensive type reflectors for local lighting. The intensities vary between 2 and 4 foot-candles with an average of 2.8 foot-candles.

WIRING.

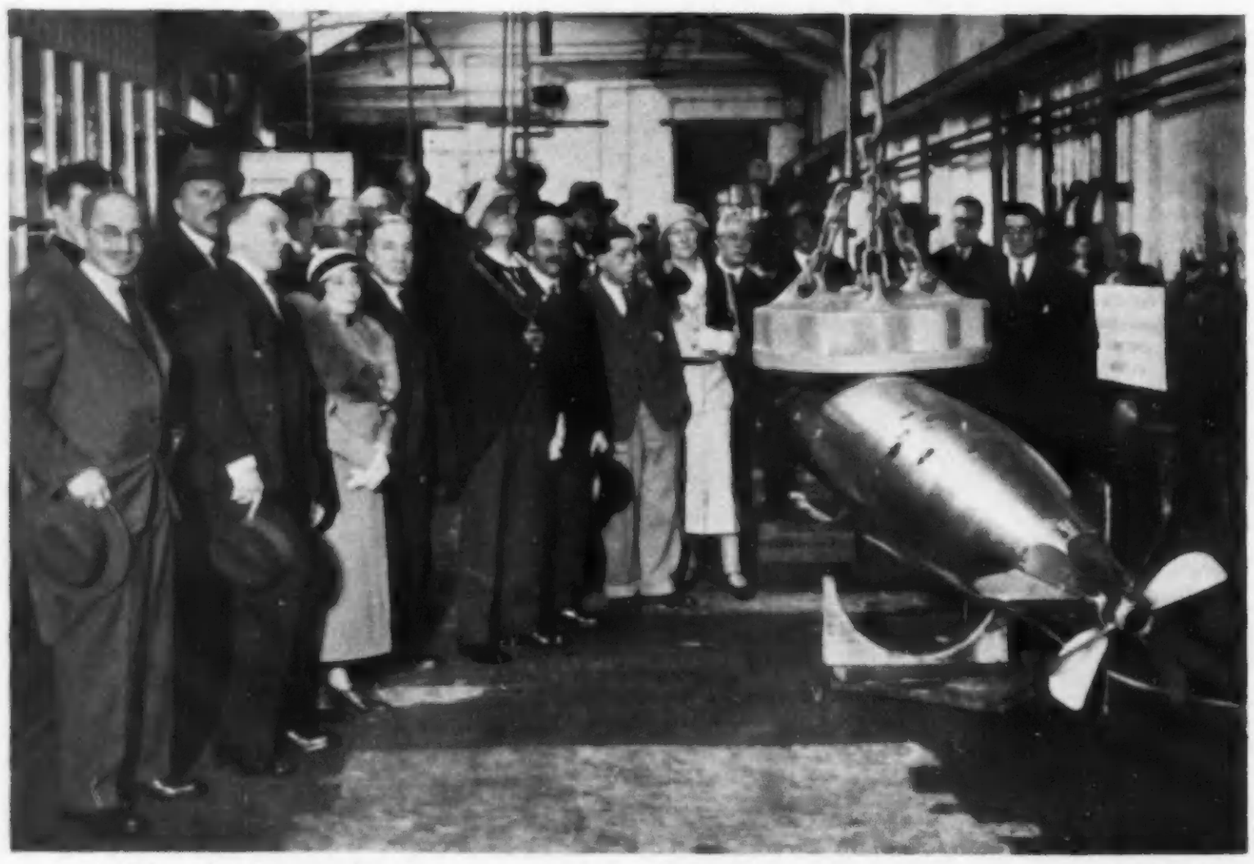
The wiring is carried out on the well known Magnet Bond system, incorporating metal sheathed wires and cables, with a continuous copper earth bonding wire running under, and in direct contact with, the metal sheath throughout.

Upwards of 25 miles of wire have been used in the installation. The wires are carried throughout on teakwood battens, those battens between the roof girders (which are spaced 11 ft. apart) are $2\frac{1}{2}$ in. by $1\frac{1}{2}$ in. by 11 ft. long and are fitted in between the beams with a $1\frac{1}{2}$ in. by $\frac{3}{4}$ in. batten running under, and fixed to the larger batten serving as an extra support and making a secure method of fixing the line of battens to the girders.

Combined switch and distribution fuse boards of the ironclad totally enclosed type are mounted on columns down the main centre passage of the mill, and from these distribution points wires radiate to the lines of lights. The switches in the distribution boards, which control the individual lines of lights are, however, seldom used as the practice is to control the various departmental lights from the main switches in the substation.

In conclusion, the author wishes to acknowledge the valuable assistance rendered to him in the preparation of this article by Mr. J. Robertson, Manager of the Bansberia Jute Mills, and desires also to acknowledge the courtesy extended to him by Messrs. MacNeill & Co. who granted permission to publish this article and the accompanying illustrations

Electro-magnet for Retrieving Torpedoes.



The Lord Mayor of Birmingham during a recent visit to the Witton Engineering Works of the G.E.C., operated an electro-magnet designed for the Admiralty to retrieve torpedoes from the bed of the sea.

The Choice of Direct Current Armature Windings.

By R. G. JAKEMAN, D.Sc., M.I.E.E., Chief Electrical Designer and J. R. HENDERSON, B.Sc., Design Dept.

Witton Engineering Works of The General Electric Co. Ltd.

In the accompanying article, the authors explain a simple method they have evolved of determining the type of armature winding most suitable for any particular frame size of direct current motor or generator.

Whilst it is realised that a contribution of this kind is limited in its appeal, it is felt that engineers engaged in the study of electrical design will find it of interest and help.

IN the design of D.C. dynamos and motors, one of the first things to be considered is a suitable type of armature winding, that is, whether wave, lap or series-parallel, and how many turns per segment are required.

Assuming that a line of frame sizes has been standardised, the frame size to be used is immediately settled by the output specified. Since the flux for a given frame size is fixed, the number of armature conductors can further be determined from the voltage and speed. It may now be found that if a wave winding be selected, the value of the average volts per segment is too high, while a lap winding may give too many segments for the standard diameter of commutator.

It is therefore clear that two limits arise which are of great importance in the design of the machine. One is the maximum permissible value of the average volts per segment and the other the minimum permissible width of segment.

LIST OF SYMBOLS.

In the subsequent calculations the following symbols are used :—

ϕ = flux per pole in megalines.
V = terminal voltage.
n = revolutions per minute.
D_c = diameter of commutator in cm.
τ_c = pitch of segment in cm (copper + mica).
C = number of commutator segments.
e_c = average volts per segment.
N = total number of armature conductors.
t = number of turns per segment.
p = number of pairs of poles.
a = number of pairs of paths in armature.

VOLTAGE EQUATION.

The voltage equation* of a d.c. machine is

$$V = \frac{p}{a}\frac{\phi N n}{6000} \qquad (1)$$

* The terminal voltage is used in this equation instead of the induced e.m.f. in order to make it hold for either a motor or generator. The necessary correction can easily be made in the final result.

This may be written

$$n = \frac{V \cdot 6000}{\phi N}\frac{a}{p} \qquad (2)$$

or

$$\frac{V}{n} = \frac{\phi N}{6000}\frac{p}{a} \qquad (3)$$

In the problem usually presented to the designer, the quantities V and n are specified, so that the right-hand side of equation (3) has a fixed value.

The voltage equation may also be written

$$\frac{V}{n} = \frac{(2p\phi) \cdot N}{2a \cdot 6000} \qquad (4)$$

The quantity $(2p\phi)$ is the total magnetic loading of the machine and for any one machine has a definite value if full use is to be made of the active material.

MAXIMUM PERMISSIBLE VALUE OF THE MEAN VOLTS PER SEGMENT.

The mean voltage per turn in the armature is $\frac{2p\,\phi \cdot n}{3000}$, so that the mean voltage per segment $= e_c$

$$= \frac{2p\phi \cdot n \cdot t}{3000}\frac{p}{a}$$

From this equation it will be seen that if a maximum limit is placed on e_c, there is a maximum possible value of the speed, n, for a given machine and a given type of winding.

This maximum possible speed is therefore

$$n_{max} = \frac{3000 \cdot e_{c\,max}}{2p\phi \cdot t}\frac{a}{p} \qquad (5)$$

MINIMUM PERMISSIBLE WIDTH OF COMMUTATOR SEGMENT.

Equation (2) may be written

$$n = \frac{2a \cdot V \cdot 6000}{2p\phi \cdot 2t \cdot C}$$

The pitch of the segment (including mica) is

$\tau_c = \frac{\pi D_c}{C}$, so that

$$n = \frac{\tau_c \cdot a \cdot V \cdot 6000}{\pi D_c \cdot 2p\phi \cdot t}$$

It will be seen from this equation that if a minimum limit is placed on τ_c, there is a minimum possible speed, n, for a given machine with a given diameter of commutator, a given type of winding and a given voltage.

This minimum possible speed is therefore

$$n_{min} = \frac{6000 \cdot V \cdot a \cdot \tau_{c\,min}}{\pi D_c \cdot 2p\phi \cdot t} \qquad (6)$$

PRACTICAL LIMITS.

As practical limits* for standard machines, we will assume that e_c must not exceed 15 volts, and that τ_c must not be less than 0.45 cm.

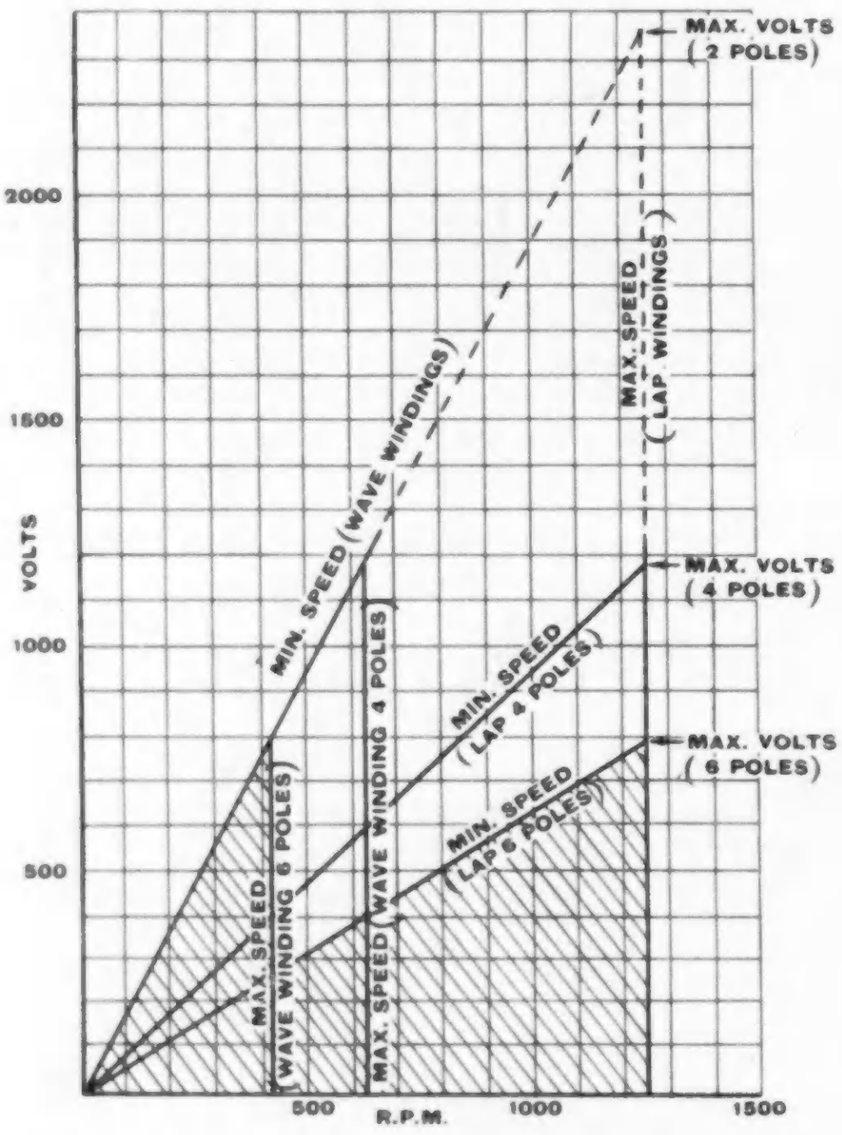


Fig. 1.—Chart drawn for one particular frame size. Magnetic loading $2p\phi = 36$ megalines; $D_c = 45$ cms; $e_c = 15$ volts max; $\tau_c = 0{\cdot}45$ cm. min.

Equation (5) then becomes

$$n_{max} = \frac{45000}{2p\phi \cdot t} \frac{a}{p} \qquad (7)$$

and equation (6) becomes

$$n_{min} = \frac{860 \cdot V \cdot a}{D_c \cdot 2p\phi \cdot t} \qquad (8)$$

SIMPLIFIED CHARTS.

Consider the above equations as applied to one particular frame size, (*i.e.* by taking definite values of $2p\phi$ and D_c), using only single-turn windings (*i.e.* $t = 1$). A simple chart can now be developed from which it can be seen at a glance whether it is possible to find such a winding which will be suitable for the specified voltage and speed in this particular frame.

Suppose the frame which is the correct size for the required output has a normal magnetic loading of $2p\phi = 36$ megalines, and let the diameter of the standard commutator be 45 cm. (The maximum permissible number of commutator segments is $45\pi/0.45 = 314$).

Then

$$n_{max} = 1250.a/p \qquad (9)$$

and

$$n_{min} = 0.53.V.a \qquad (10)$$

The following table shows these values for lap and wave windings for 2, 4 and 6 poles.

	p	a	a/p	n_{max}	n_{min}	V_{max}
2 pole lap or wave ..	1	1	1	1250	0.53V	2360
4 pole lap	2	2	1	1250	1.06V	1180
4 pole wave	2	1	½	625	0.53V	1180
6 pole lap	3	3	1	1250	1.59V	785
6 pole wave	3	1	½	417	0.53V	785

The figures in this table have been plotted in the form of a chart (Fig. 1). It will be seen that the values of n_{max} are vertical straight lines, while the values of n_{min} are straight lines passing through the origin. The points of intersection of the n_{max} and n_{min} lines are obtained by equating equations (9) and (10), which gives $V_{max} = 2360/p$, the values of which have been added to the table. In this way the chart can be constructed with ease.

The value of V_{max} can also be obtained from the usual equation for the volts per segment $e_c = 2pV/C$. Inserting the maximum values of e_c and C, this can be written $V_{max} = e_{c\,max} \cdot C_{max}/2p$, which becomes in this case $V_{max} = 15 \cdot 314/2p = 2360/p$.

METHOD OF USING SIMPLIFIED CHARTS.

The chart in fig. 1 has been drawn for one particular frame size, having a magnetic loading of $2p\phi = 36$ megalines. It is therefore necessary to draw a similar chart for each standard frame size.

Suppose it is desired to design a machine for which the frame size used for fig. 1 is correct. Referring to the chart (fig. 1), the point of intersection of the horizontal through the supply voltage and the vertical through the specified speed is found. If a particular winding is possible, this point of intersection must lie to the right of the n_{min} line for that winding and to the left of the n_{max} line for the same winding.

For example, if the voltage is 500 and the speed 1000 r.p.m., either a 4 pole or 6 pole lap winding

* These values are intended as a guide only. Actual limits must be determined in the light of experience and may vary according to the size of the machine.

could be used. (The chart includes a 2 pole winding for the sake of completeness, but it is unlikely that the same frame size would be used for 2 and 6 poles).

If the voltage is 500 and the speed 700 r.p.m. a 6 pole lap winding would not be possible, since the point of intersection lies to the left of the n_{min} line. A 4 pole winding could be used.

In this case, however (500 volts, 700 r.p.m.), it would be possible to use a 6 pole lap winding, if a commutator of larger diameter could be fitted. Fig. 1 is drawn for a commutator diameter of 45 cm, but if the diameter is increased, the n_{min} line is raised in proportion (see equation (8)). The diameter necessary for a 6 pole lap winding for 500 volts, 700 r.p.m., would be $45(500/440) = 51$ cm.

As a further example, for 500 volts, 500 r.p.m., a 4 pole wave winding would be required.

The shaded area in fig. 1 shows the very limited sphere of the 6 pole winding with single-turn coils. If it is considered desirable to use 2-turn coils, n_{max} is 625 r.p.m. and V_{max} is 785, so that a corresponding n_{min} line can be added to the chart. This has been omitted for the sake of clearness. Even if 2-turn windings were to be used, the requirement of 500 volts, 700 r.p.m. could not be obtained from a 6 pole machine of this frame size without increasing the diameter of the commutator.

If the specified speed is higher than the n_{max} line for lap windings, no suitable winding can be found unless the selected limit of 15 volts for the mean volts per segment is exceeded. This difficulty may in some cases be overcome by using a compensating winding in the pole-face. In other cases it may be cheaper to use a different frame size.

for 6 poles, and n_{min} lines have been drawn for three different diameters of commutator. The maximum voltage for these charts is $V_{max} = 52.3 \cdot D_c/p$.

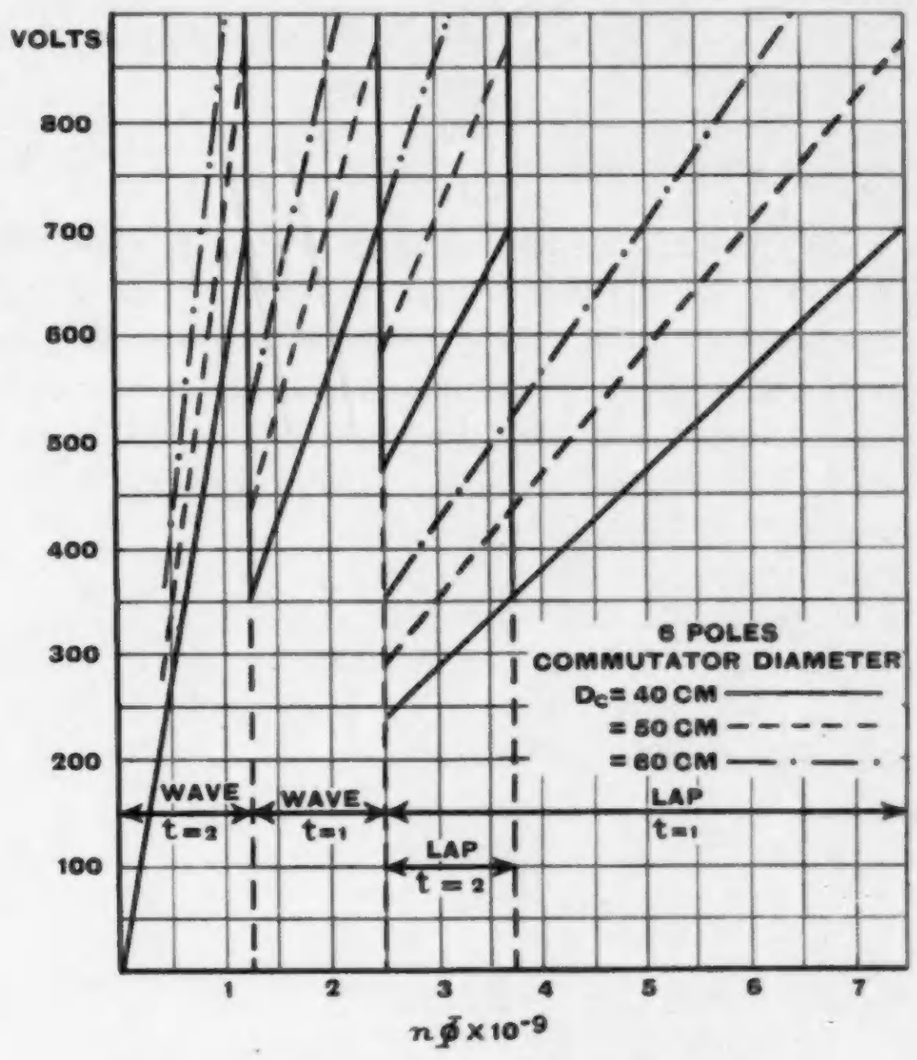


Fig. 2.—Chart drawn for 6 poles and for three different sizes of commutator.

ALTERNATIVE CHARTS.

According to their method of classification, some designers may find it more convenient to make one chart for each number of poles, instead of one for each frame size.

Equations (7) and (8) can be written

$$n_{max} \cdot \phi = \frac{45000}{2p \cdot t} \frac{a}{p} \quad (11)$$

$$n_{min} \cdot \phi = \frac{860 \cdot V \cdot a}{D_c \cdot 2p \cdot t} \quad (12)$$

By plotting $n\phi$ against the voltage, a new chart can be prepared for each number of poles. Fig. 2 is a chart

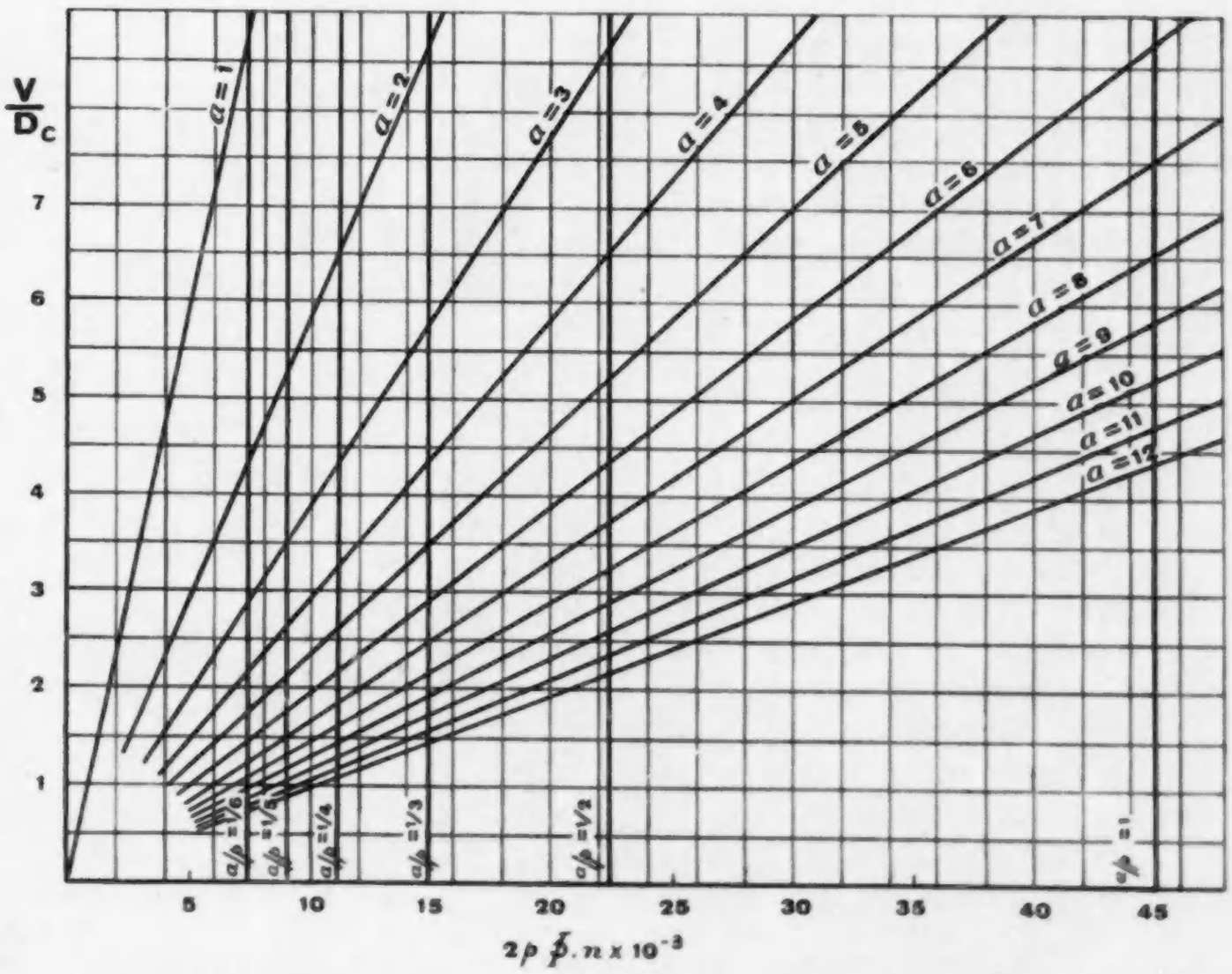


Fig. 3.—Chart which can be used for any frame size, any number of poles and any diameter of commutator.

GENERAL CHART.

Proceeding one step further, a chart can be drawn which can be used for any frame size, any number of poles and any diameter of commutator.

Equations (7) and (8) can be rewritten

$$n_{max} \cdot 2p\phi = \frac{45000}{t} \frac{a}{p} \qquad (13)$$

$$n_{min} \cdot 2p\phi = \frac{860}{t} \cdot a \cdot \frac{V}{D_c} \qquad (14)$$

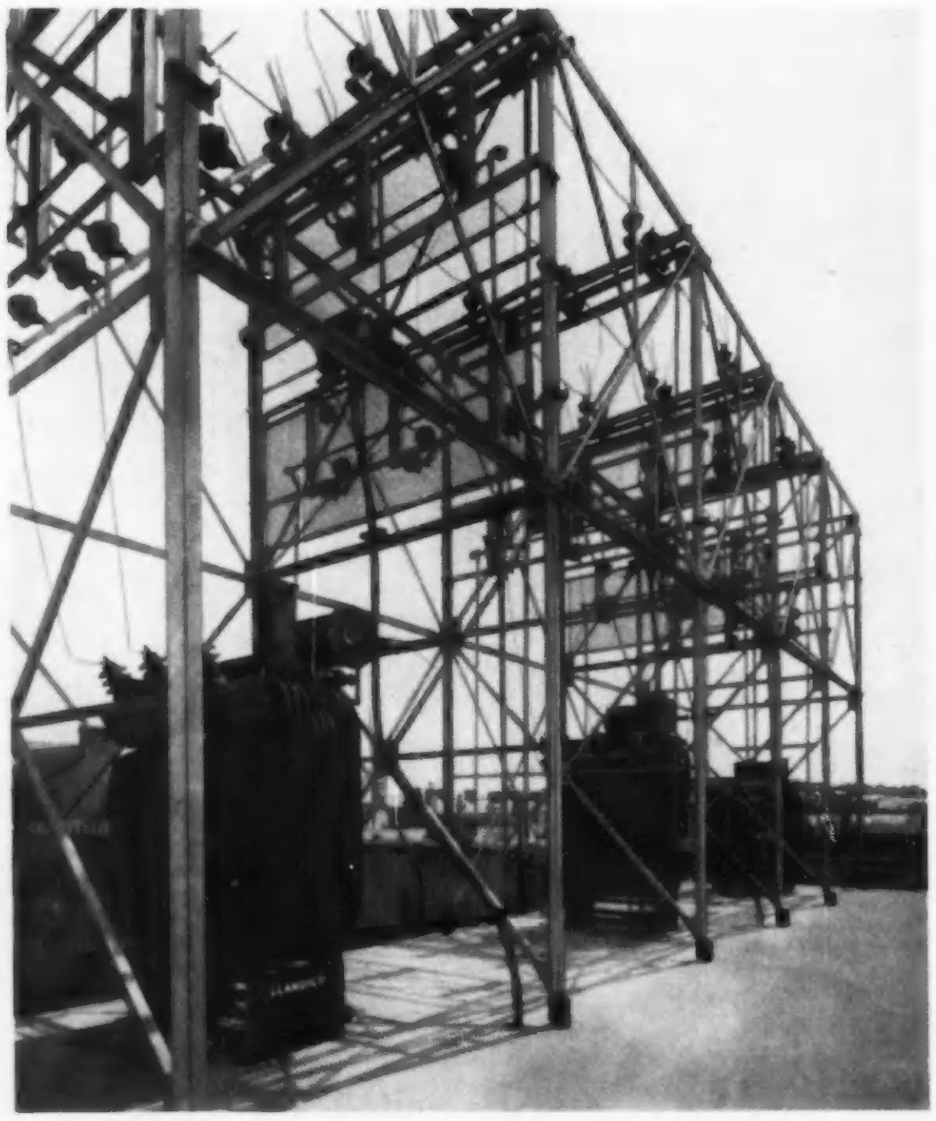
By plotting $n \cdot 2p\phi$ against V/D_c, a chart is produced which holds for any number of poles, any frame size and any diameter of commutator. Fig. 3 shows this chart which is drawn for single-turn windings only. It could be used for any number of turns by drawing n_{min} lines for all values of a/t and n_{max} lines for all values of a/pt. This, however, would complicate the chart, and it appears better to have a separate chart for each number of turns.

The general chart is especially useful for larger frame sizes, where it may be found convenient to use series-parallel windings.

As an example, let $2pn\phi = 19200$, and $V/D_c = 4.9$, and let the standard number of poles for the frame size selected be 12. It will be seen that a lap winding is impossible, since the point of intersection lies to the left of the n_{min} line for $a = 6$. A series-parallel winding, however, would be feasible, since the point of intersection lies between the n_{min} line for $a = 3$ and the n_{max} line for $a/p = \frac{1}{2}$. If it is not desired to use a series-parallel winding, it is possible to use an 8-pole machine with a lap winding, since the point of intersection lies between the lines $a = 4$ and $a/p = 1$.

A further use of the general chart is to select a suitable number of poles in the case of large machines. If $2pn\phi = 36{,}000$ and $V/D_c = 5.6$, the maximum number of poles possible is 14, since the point of intersection lies to the left of the n_{min} lines for which a is greater than 7. Alternatively, if it is found more convenient to use a 16 pole machine, the diameter of the commutator must be increased to bring the point of intersection below the line $a = 8$.

Outdoor Switching and Transforming Station at Carmarthen.



General view of the 22 kV outdoor sub-station of The West Cambrian Power Co., at Carmarthen. The equipment includes remote operated horn air-break switches, vertical gang operated air-break switches, and trifurcating boxes. The three transformers are each 500 kVA, 11/22 kV.

Communication, Protection and Supervisory Control Systems for Electric Power Networks.

By Engineers of G.E.C. Telephone Works, Witton Engineering Works, and Pirelli-General Cable Works.

No more significant example of the benefits secured by close co-operation between highly specialised branches of the electrical industry is to be found than in recent developments in the field of power transmission and distribution. This article, based on the combined work of various sections of the G.E.C. Organisation, forms a general survey of what may be termed the communication requirements of power undertakings and will be followed in a later issue by more detailed reference to modern systems and their application to typical power networks.

INTRODUCTION.

PROGRESS in the methods of transmitting power by electrical means for industrial and other purposes has been so rapid and spectacular in the past twenty years or so that it is sometimes overlooked that development in "light current" electrical transmission has been equally rapid, and that as a result the "light current" engineer has reached the position where he can offer to his "heavy current" colleague facilities which, though for many years known to be desirable, have in most cases been economically impracticable. Improved means of electrical communication both by spoken word and printed message; more stable and efficient methods of feeder protection; reliable devices for the indication at any distance of switch conditions, meter readings and the like; remote control systems which, even in the event of their failure (a possibility which must not be neglected) cannot perform a false operation; all these are now at the disposal of the power transmission engineer. Moreover, these facilities are not only available at a cost which can be balanced actuarially to advantage against saving in labour and other charges, but they provide incalculable advantages in the improved reliability of the transmission system to which they are applied.

The improved systems available to-day are the result of development work partly on power networks, but mostly in the field of communication engineering, and employ well-known basic methods of signal transmission and apparatus well proved in telephony, telegraphy and allied arts, modified and adapted to suit the particular requirements of Power Undertakings both large and small.

These requirements vary not only with the transmission voltage but also depend upon the executive control plan, layout, and even the locality of the network. In consequence, the planning of the communication service and control system best suited to any main transmission or local distribution scheme requires the careful investigation of a large number of considerations and it is proposed in the following pages to outline the services necessary to the efficient operation and control of a power network and the communication channels which may be employed to provide them. Account will also be taken of the factors governing the services for which any particular channel can be used, and finally a more detailed description will be given of the systems and apparatus which may be employed in typical networks.

REQUIREMENTS OF A POWER SYSTEM.

In respect of communication, supervisory control and certain forms of feeder protection, the requirements of a power undertaking operating an interconnected network may be summarised as follows :—

(1) The passage of instructions between the control and subordinate personnel. This may be accomplished by

- (*a*) Telephone
- (*b*) Teleprinter
- (*c*) A visual indicator of the "engine-room telegraph" type.

(2) Feeder protection, where the apparatus employed is of the type requiring a communication channel between the ends of the section of feeder to be protected.

(3) Facilities enabling the control operator to open and close switches at distant substations or to bring in and cut out generating plant.

(4) Automatic indication to the control operator of the position or condition of any piece of apparatus at a distant substation or generating station.

(5) Facilities enabling the control operator to read meters at distant stations.

COMMUNICATION CHANNELS.

Each of the foregoing services requires a channel

of communication and the economic provision of these channels is of considerable importance. The channels available employing pilot wires may be summarised as follows :—

(1) A buried armoured cable.
(2) Aerial wires erected on the same supports as the power conductors, if the power line is overhead.
(3) Aerial wires carried on a separate pole line.
(4) An aerial cable, suspended from a catenary wire attached to the overhead transmission line supports.
(5) An aerial cable carried on a separate pole line.
(6) An overhead earth cable, the core of which is formed by insulated pilot wires.
(7) Lines rented from the public telephone administration.

In addition to the above, two further means of

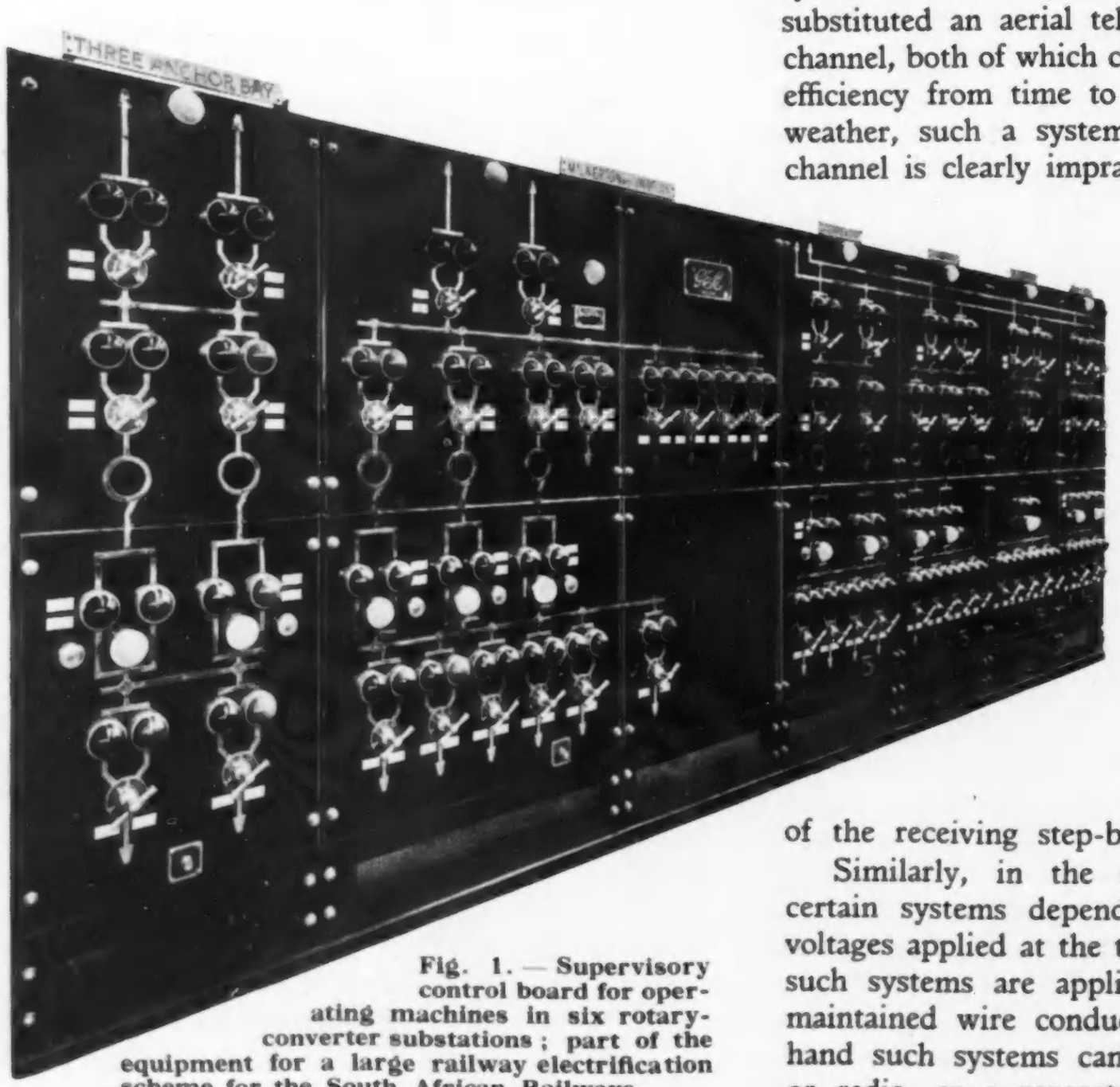


Fig. 1. — Supervisory control board for operating machines in six rotary-converter substations ; part of the equipment for a large railway electrification scheme for the South African Railways.

communication may be considered, not requiring the use of pilot wires, *i.e.*

(8) Carrier currents superposed in overhead power lines.
(9) Radio.

SERVICES AND CHANNELS.

Generally speaking it is possible to provide over these channels any of the services outlined under the heading of "Requirements," but there are certain exceptions.

These are usually cases where a quantitative method of transmission is required over a channel whose transmission efficiency is not perfectly constant. For example, the transmission of an ordinary telegraph signal is practically independent of quantity in that so long as the minimum signal to operate the receiving apparatus is received, increases in strength of the signal within reasonable limits will usually have no effect upon accuracy of reception. On the other hand one may imagine a system of remote metering, where the receiving instrument is supposed faithfully to indicate the variation in potential applied at the distant end of the line. So long as the transmission efficiency of the line is constant, a condition which may be presumed to obtain in the case of a buried pilot cable of good insulation, the system is workable, but if for such a pilot cable is substituted an aerial telephone circuit or a carrier channel, both of which channels vary in transmission efficiency from time to time due to the action of weather, such a system of metering over such a channel is clearly impracticable.

If, on the other hand, the system of metering adopted is one which relies upon a step-by-step system, where the number of steps transmitted over the channel is an indication of the position of the instrument at the transmitting end, then this system can be effective even over a channel of varying transmission efficiency, provided that the strength of the received signal never falls below or exceeds the working limits of the receiving step-by-step mechanism.

Similarly, in the case of feeder protection, certain systems depend upon balancing opposing voltages applied at the two ends of the channel and such systems are applicable to any form of well maintained wire conductor circuit. On the other hand such systems cannot be operated by carrier or radio, as a separate frequency channel would be required in each direction to indicate to the distant end a measure of the voltage to be transmitted and it is impracticable to maintain carrier or radio channels of different frequencies at equal or constant ratios of transmitting efficiency. Again, there are systems of feeder protection which depend not upon

the transmission of a measured quantity, but upon the transmission or non-transmission of a definite signal. Such systems are, of course, applicable to any kind of channel as within the working limits of the receiving apparatus the amplitude of the signal is of no importance.

Perhaps enough has been said to indicate that in planning the provision of services, account must be taken not only of the services desired but of the types of channels available or which may be economically installed.

The consideration of traffic requirements is similarly important and must not be ignored. If, for instance, a channel is not fully occupied it represents a certain loss to the user which may be avoided by employing one channel for several services, arranging that each occupies the channel as required. This postulates some form of priority.

Given a channel of communication, the characteristics of which will permit of its use for telephone or telegraph, remote control, supervision and remote metering, these four services may be operated over the single channel, the technical arrangements being sufficiently flexible to give any priority required. It may, however, be undesirable to combine feeder protection with many other services on the same channel, but experience has shown that when employing certain feeder protection systems the channel provided can be used also for simple telephone or telegraph communication, arrangements then being made so as to ensure the instantaneous seizure of the channel for the transmission of protection signals as and when required.

While economy can thus be introduced in the cost of communication channels by the grouping of services, it is nevertheless conceivable that the amount of traffic in certain circumstances would not permit the application to one channel of as many types of services as is technically possible. It therefore becomes necessary to study also the operating conditions obtaining in the network, the result of which might even lead to the balancing of the advantages of a facility which may be desirable but not indispensable against the cost of providing an additional channel in order to obtain it.

So again it must be emphasised that the fullest consideration of a large number of factors is essential in every case to the planning of the most suitable scheme.

DETAILED CONSIDERATION OF CHANNELS.

Apart from the instability of certain channels to which reference has already been made, and their consequent unsuitability for particular types of services, there will obviously be advantages attaching to some and disadvantages to others in every case where the conditions in a specific power network are under consideration. Some of the principal features and limitations of the various possible channels outlined will therefore be discussed in greater detail.

BURIED ARMOURED CABLE.

A buried armoured cable will provide communication channels which, apart from breakdown of the cable itself—a possibility comparatively remote—are immune from disturbance of any kind. Such a cable can consist of several pairs of conductors, thereby affording an adequate number of channels and allowing the provision of many simultaneous facilities. By careful balancing between the various cable lengths, a high-grade telephone circuit can be obtained and it is possible also to operate feeder protection systems of the 50 cycle A.C. type over the same cable without disturbing the adjacent telephone circuit.

If the power lines are overhead, the cost of the armoured cable will be considerably increased by the burying and reinstatement charges which will vary widely according to the type of excavation. The same applies if the power lines are underground and the communication channels are added at a later date.

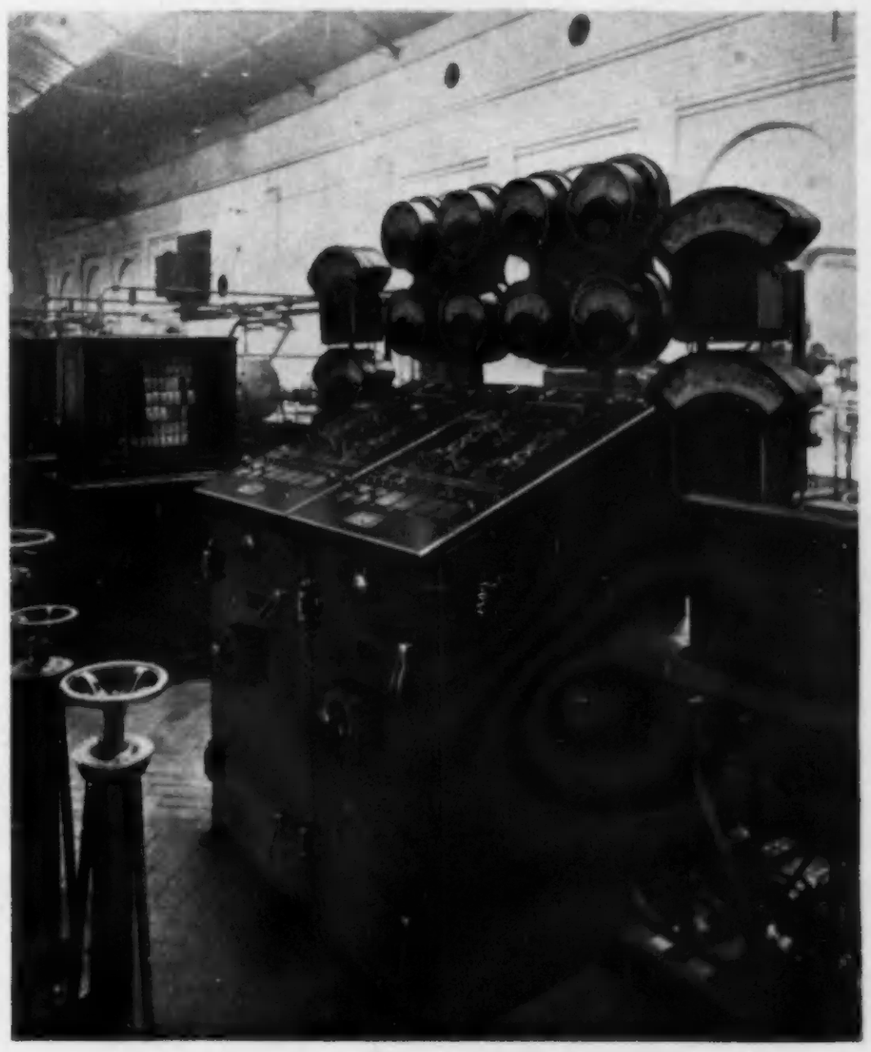


Fig. 2.—Control panel and supervisory cabinets in generating station of Southend-on-Sea Corporation.

Buried cable is economical when it is used in conjunction with underground feeders and is laid in the same trench and at the same time as the underground power cable. Where the country is open it may be economical to lay buried cable for use with overhead lines, but even with up-to-date cable

laying machinery (which digs a trench, lays the cable and reinstates in one operation), the costs are likely to exceed those for an aerial cable attached to power line supports.

AERIAL WIRES ERECTED ON OVERHEAD TRANSMISSION LINE SUPPORTS.

It is possible to erect communication conductors on the supports which carry the transmission line, but this practice is usually restricted to lines up to 33 kV. Care has to be taken to provide adequate clearances between the power and communication conductors and also between the latter and ground.

Fig. 3.—Control panel and supervisory cabinet at Parker Street substation controlling rotary converters at Granville Street substation (Birmingham Corporation).

Difficulties are then likely to be experienced if long spans are encountered and the cost of the power line will be increased on account of the necessity for higher supports.

Communication conductors erected in this manner require frequent transposition if they are to be used for telephonic purposes and even with such transpositions the circuits are liable to be noisy. Background noise might even, on occasions, reach such a level as to render speech unintelligible, and the practice of erecting aerial conductors on the power line supports is therefore not recommended where a commercially silent telephone service is required. Such conductors would, however, be suitable for teleprinter or other facilities unless the interference were extremely heavy.

AERIAL WIRES ON A SEPARATE POLE LINE.

Aerial conductors erected on separate poles adjacent to a power transmission line are subject to inductive disturbances and require frequent transposition if used for telephony. It is nevertheless difficult to obtain a silent telephone circuit, though the interference is not likely to be so pronounced as to prevent other services being given.

A separate pole line will not usually have the same mechanical strength as the power line and may therefore be subject to interruption by storms which would leave the power line intact. It is a serious matter if the channel used for controlling the power line is interrupted while the latter is still in service and this method, therefore, cannot be recommended.

AERIAL CABLE CARRIED ON TRANSMISSION LINE SUPPORTS.

The suspension of an aerial type of cable from a catenary wire attached to the transmission line supports is a satisfactory manner in which to provide communication channels for overhead lines up to 33 kV, and it can be employed for lines up to 66 kV, if the tower spacings and height permit the catenary wires to be satisfactorily erected.

As in the case of a buried cable a number of conductors can be provided to give several facilities simultaneously. The two wires of each pair being close together considerably reduces the inductive disturbance due to the power line, thus enabling a high-grade telephone circuit to be obtained.

The cable, being suspended on the transmission line supports, possesses the same factor of safety as the line itself and communication is not likely to be affected by weather conditions. It is also possible to erect such a cable on an existing power line and so suspend it, in relation to the phase wires and ground, as to maintain the necessary clearances.

AERIAL CABLE ON A SEPARATE POLE LINE.

If an existing power line be considered, having physical limitations which prevent the erection of an aerial cable on the transmission line supports and it is desirable to maintain throughout the whole network a cable channel of communication, a separate pole line may be employed. While this arrangement is in all other respects as satisfactory as the suspension of aerial cable from the supports of the power line, the separate pole line might be more liable to damage by accident.

COMBINED PILOT AND EARTH WIRE CABLE.

There has been recently introduced a special type of aerial cable which serves both as an earth wire for the power circuits and as a pilot cable. The core consists of up to four insulated wires, sheathed in lead and surrounded by a layer of galvanised steel wires.

A cable so formed has sufficient longitudinal strength to require no supporting catenary wire, is fully protected from damage both during and after erection by the layer of steel wires, and offers the

least possible area to wind pressure, thereby reducing to a minimum the additional load imposed on the power line supports on which it is erected. The particular field of application of the cable is as a substitute for a plain earth conductor on an overhead power transmission line where not more than two pilot or telephone pairs are required and especially where the permissible additional loading of the supports is limited.

LINES RENTED FROM TELEPHONE ADMINISTRATION.

One or more pairs of wires may be rented from the Administration responsible for the public telephone service and the channels so obtained may be :—

(1) Aerial conductors entirely.
(2) Mixed aerial and cable pairs.
(3) Cable wires throughout.

All the required communication facilities may be provided over such channels, but, when long circuits are encountered, they may include transformers or telephone repeaters and so necessitate the use of alternating currents in the voice frequency range for obtaining facilities other than telephony.

From an economic point of view, the rental may be heavy, while there are also certain other disadvantages attached to the use of rented telephone lines. The maintenance and supervision of the communication network becomes divided, very stringent

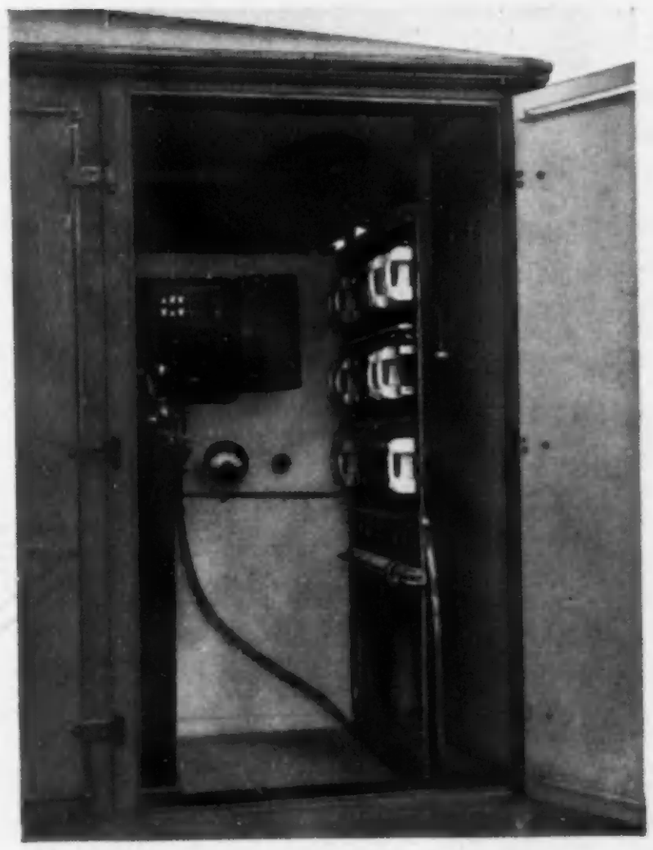


Fig. 4.—Interior of L.T. compartment of transformer kiosk (refer to fig. 5), showing supervisory apparatus cabinet at the back of the cubicle.

safeguards may be demanded by the telephone administration to prevent the possibility of high tension voltage reaching the communication channel, and, if the lines are repeatered or contain transformers, the capital cost will be increased by the provision of the necessary voice-frequency signalling equipment. Further, the lines will in all probability follow a route occupied also by a large number of other circuits owned by the telephone administration and will therefore be subject to possible interruption during maintenance or repair work affecting any of the line plant along that route.

Fig. 5.—Supervisory control cabinet at Worksop Corporation Power Station for operation of transformer kiosk system.

CARRIER CURRENTS SUPERPOSED ON OVERHEAD POWER LINES.

Considerable progress has been seen in recent years in the development and application of communication systems employing either modulated or interrupted high frequency currents superposed on lines already used for other purposes. A power transmission line may carry, not only the power energy at the commercial frequency, but also carrier energy at a relatively high frequency of the order of 50 to 200 kilocycles per second. Such carrier circuits can be employed for remote control, remote indication, remote metering and also for feeder protection systems of the D.C. impulse type. At the same time, the channel may be used for speech by modulating the carrier current by the speech currents at one end and demodulating at the other. At the ends of each section of the power line suitable devices are inserted for the separation of the low and high frequency energy, the low frequency power being directed to the switchgear and the high frequency to the communication apparatus.

Since the provision of a carrier communication channel involves only the addition of terminal carrier equipment and requires no auxiliary line plant other than the separating devices, its cost is

independent of the distance between any two stations. As a result, a carrier system can be employed with definite economic advantage where the switching points in a power network are widely separated. On the other hand if the stations are close together, it may be less expensive to provide pilot wires or cable.

RADIO COMMUNICATION.

The use of radio telephony or telegraphy is possible but may lead to difficulties with regard to wavelength allocation in congested areas. Short wave lengths may be employed to overcome this but unless the stations are some distance apart communication may be unreliable, particularly if one point comes within the "skip distance" of another.

While in many fields radio telephony has proved highly successful and dependable, it should also be noted that atmospheric disturbances are liable to have a much more serious effect on the transmission and reception of signals than on speech. Interference which may cause only slight interruption during conversation might on the other hand result in the loss on an important control signal and lead to serious consequences.

Generally speaking, experience has shown that requirements which can be met by a radio system can be satisfied with greater advantage by either pilot or carrier working.

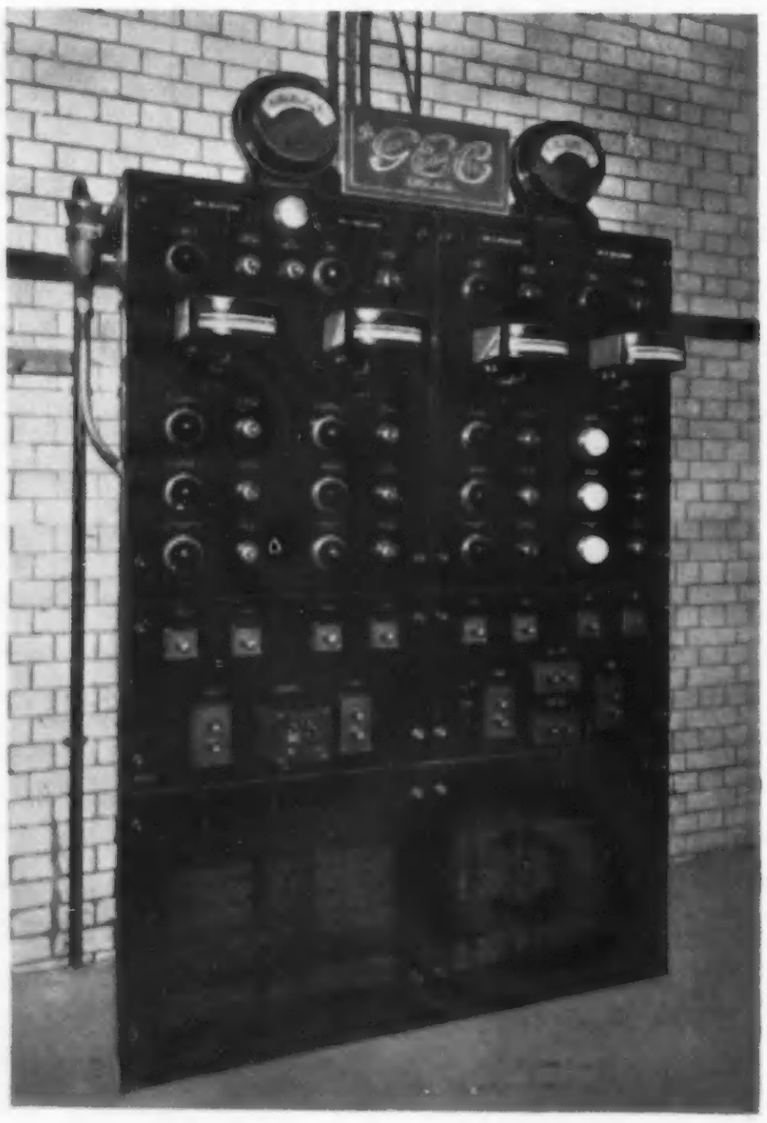


Fig. 6.—Remote control board at Short's Garden Generating Station of the Charing Cross Electricity Supply Co., Ltd.

DETAILED CONSIDERATION OF SERVICES.

So rapid has been the development of systems whereby the control of equipment at one or more remote points can be concentrated at a central station or office, that the variety of facilities that can be provided is almost unlimited. Having already outlined briefly the principal communication services necessary to the efficient and economic operation of a power network, including under this heading systems of feeder protection which also utilise a communication channel, it is proposed now to deal with these services in greater detail.

TELEPHONE AND TELEGRAPH.

Various methods may be employed for providing telephone communication between a number of points, the choice of system depending entirely upon the layout of the power network, the channels available and the precise nature of the service desirable. For example, a comprehensive scheme may be adopted, embracing within the system every point in the network and giving the fullest intercommunication facilities.

Such a system would necessarily involve the use of a channel between each remote point and the central office, where the switching equipment might be of either the manual or automatic type. The usual factors governing the choice of a manual or automatic system would apply, the principal consideration being that whereas the former would require an operator—and in some cases such manual control may, of course, be desirable—an automatic system would give a twenty-four hour service without attention. Cases frequently arise, however, in which some of the channels are not suitable for automatic working but are quite satisfactory for manual. For instance a metallic circuit equipped with drainage coils for line protection could be used in a manual, but not generally in an automatic system.

Should the disposition of the various points in the network be such as to permit their interconnection by a common telephone circuit, party line working could be employed to give a satisfactory service, introducing at the same time considerable economy in the cost of line plant. The use of such an arrangement is, however, generally confined to distribution schemes in which the number of stations is small.

Another system, which is now widely employed in areas containing a number of unattended switching stations, is so designed as to give intercommunication between the control office and all remote points but not between the substations themselves. Since in such an area telephonic communication is usually required only at times when maintenance work is in progress, a system of this kind will answer the requirements satisfactorily and, by means of suitable selective equipment, can be operated over

a channel providing other facilities such as remote control or indication.

For the telegraphic transmission of messages and instructions between any two points a convenient form of instrument is available in the modern teleprinter which, as distinct from Morse instruments, does not require the services of a highly skilled operator, the keyboard being similar to that of an ordinary typewriter. A valuable feature of the teleprinter is that a printed record of each message sent is left at both the transmitting and receiving ends.

For communication between a central office and distant generating plant, a telegraph of the engine room type may in certain cases prove useful, but such instruments will, of course, transmit and give visual indication of only a limited number of predetermined standard instructions.

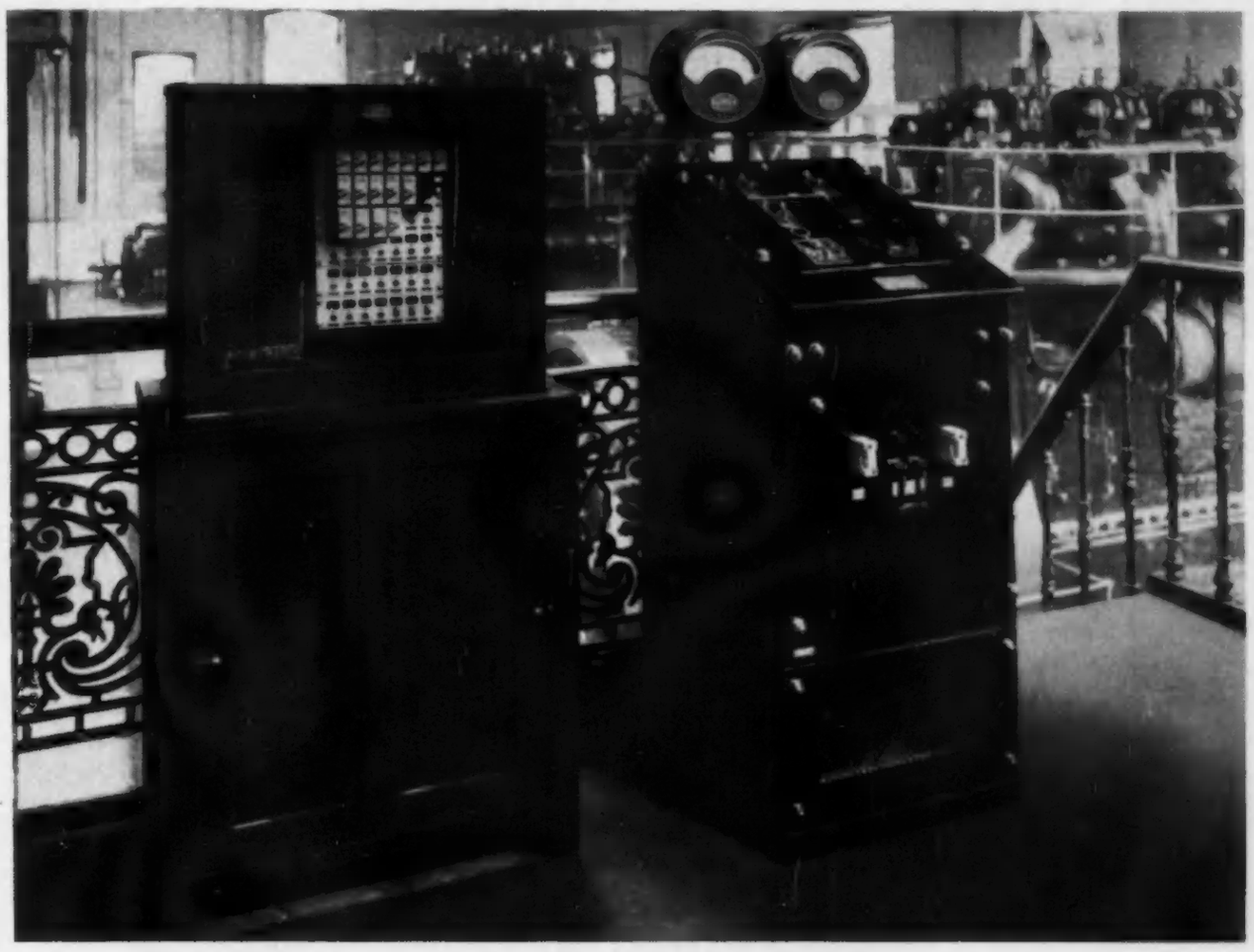


Fig. 7.—Control panel and supervisory cabinet in the generating station of the Electricity Co. of Macclesfield, Ltd., for substation converting plant operation.

FEEDER PROTECTION.

Systems of feeder protection fall into two main groups (1) those which do not require communication channels and (2) those which do. Of these, the latter only comes within the scope of this article and can in turn be divided into two classes, which may be described as (*a*) qualitative and (*b*) quantitative.

Under the heading of qualitative systems come those in which a combination of A.C. relays, operated from the current transformers at each end of the protected feeder, send a D.C. impulse (or its equivalent) over the communication channel and so cause tripping or stabilisation as required. The D.C. impulse so transmitted is independent of the magnitude of the A.C. fault current. An example of such a system is the Kapp Carrothers Duplex.

Employing quantitative transmission are those systems which compare the magnitude and phase of the current entering and leaving the protected feeder and thus require the channel to transmit some portion of the A.C. obtained from the current transformers. The characteristics of the channel employed must therefore be such as to permit the transmission of 50 cycle A.C. which in magnitude and phase follows the fluctuations in the protected feeder. On this principle is based, for instance, the well-known McColl system of protection.

It will be obvious that, when employing a feeder protection system which depends for its operation on currents constantly circulating in the protection channel while the feeder is in service, the provision of other facilities over the same channel will introduce problems of considerable complexity. In the case of systems in which the protective devices are operated by a momentary impulse transmitted over the communication channel, it is, however, possible to use the channel also for telephone purposes. Arrangements are then made so that, by the operation of relays in the event of fault conditions in the feeder, the channel is disconnected from the telephone equipment and applied to the protection gear.

Since the period during which the channel is engaged for the transmission of protection signals is less than one second, the resulting interruption of the telephone circuit is of little importance. Such interruption would, however, be inconvenient were the channel employed also for remote control purposes, since it might involve the loss or mutilation and consequent delay of an important control signal.

REMOTE CONTROL.

Perhaps the simplest method of obtaining a measure of centralised control of a number of generating and sub-stations forming an interconnected network, is to employ only a straightforward telephone system and to arrange for all operations to be performed manually in accordance with instructions telephoned from the control point. While this procedure is practicable and may adequately meet the requirements of certain networks, it does not provide the advantages offered by the more comprehensive systems which can be applied to modern plant. Further it involves the provision of staff at each station to carry out the necessary operations, whereas by the addition of other facilities to the system, and providing that the plant is of suitable design, it would be possible to

leave many of the stations entirely unattended. For instance, the usual operations effected by sub-station attendants, such as the opening and closing of switches, the starting and stopping of all kinds of converter plant and the regulation of voltage on both A.C. and D.C. distribution systems, can readily be brought under the direct control of a central station.

So far as generating plant is concerned, the application of remote control is certainly more limited, particularly in the case of steam turbo equipment, but given a source of power which involves no extremely complicated routine in its control during the process of conversion into electrical energy, then the problem of extending control to a remote point presents little difficulty. An example may be found in the systems developed for use in conjunction with hydro-electric stations.

It will be evident that the design of a system for centralising the control of equipment situated at one or more remote points will be dependent on a great number of factors, and that in no two power networks will conditions be identical. Generally speaking, however, economic considerations will demand close investigation of the cost of providing communication channels, of the amount of auxiliary equipment required and of the dependence of these items one upon the other. For example if a large number of channels were available, it would be possible to give a variety of facilities by means of relatively simple apparatus, employing one channel exclusively for each. On the other hand it is almost invariably found that it is economically or physically impossible to provide an unlimited number of channels and consequently the introduction has been seen of systems in which selective apparatus is used with the object of multiplying the number of facilities that can be given over one channel. Nevertheless, while it is now technically possible to control, for instance, a large switching station or even a group of remote unattended substations over one pair of pilot wires, the amount of selective equipment necessary may be such as so far to increase the total cost of the system that it would be more economical to provide an additional communication channel and employ less complicated apparatus.

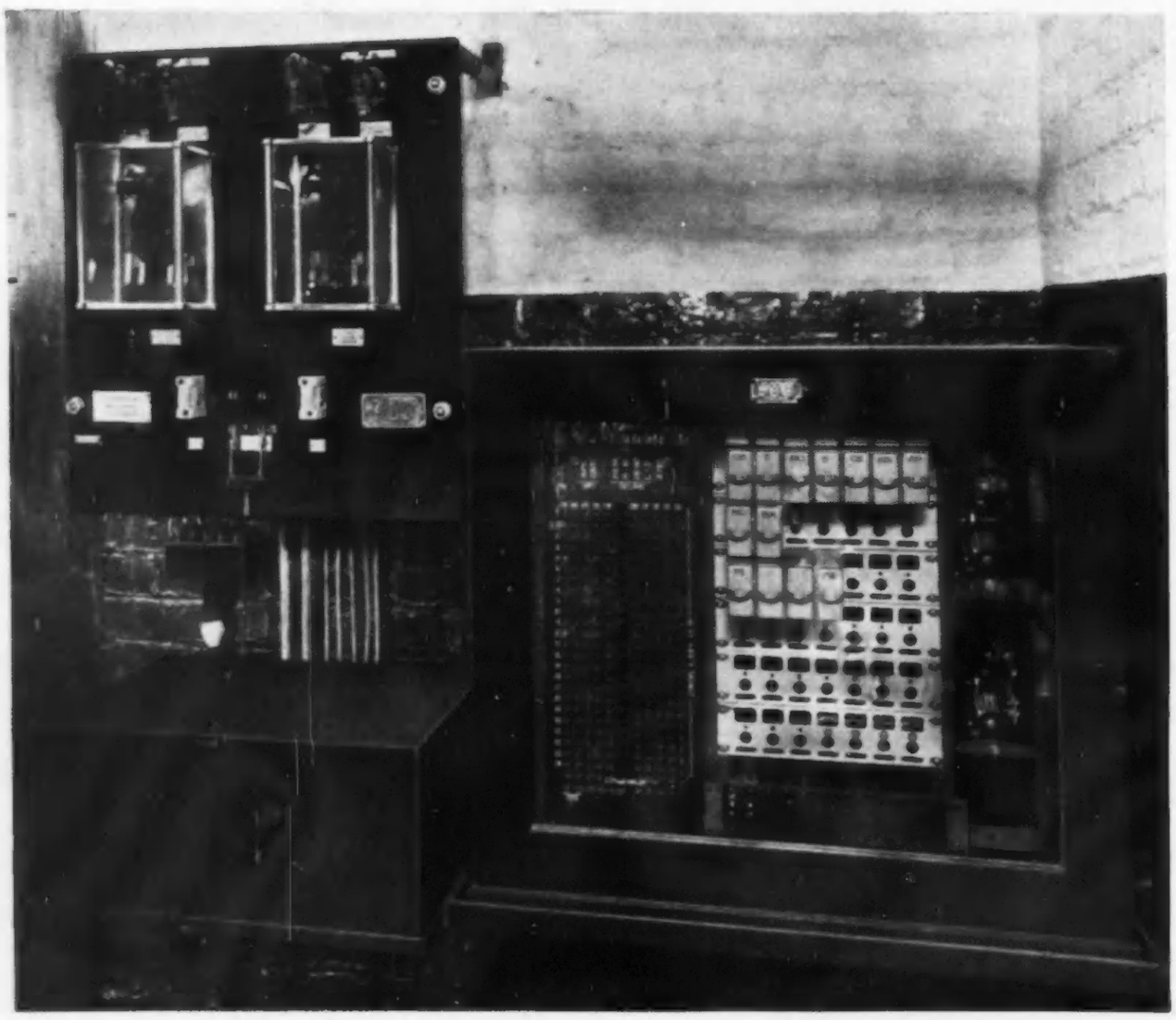


Fig. 8.—Supervisors apparatus cabinet in substation of the Electricity Co. of Macclesfield, Ltd.

The principles upon which selective systems are based are those commonly employed in automatic telephony, the signals transmitted over the channel consisting of trains of impulses, by means of which standard telephone type relays are operated, which in turn control multi-point automatic selectors. Thus, by the use of predetermined impulse combinations, any particular control gear can be selected and subsequently operated by the transmission of a further signal or signals. In order to confirm accuracy of selection, arrangements are usually made also for the transmission of a check-back signal to the control point before the operation is actually carried out.

It is worthy of note that the apparatus employed throughout these selective control systems possesses the highest degree of reliability in service, this very

essential feature having been well proved on installations in all parts of the world.

REMOTE INDICATION.

While in the foregoing paragraphs specific reference has been made to remote control only, it would in all but exceptional circumstances be impracticable to carry out operations at a distant point without the aid of facilities whereby the actual condition of the plant could be ascertained. It is therefore usual to consider remote control and remote indication together, under the title of Supervisory Control, although remote indication is a facility which can be—and often is—employed usefully by itself.

By means of the same selective equipment—and, if remote control facilities are provided, over the same channels—central indication can be obtained, either continuously or on demand, of the condition of almost any kind of plant. Provision can be made, for example, for the remote indication of the positions of oil switches, field regulators, induction regulators and transformer tap-changing gear, the state of mercury rectifiers, rotary converters and similar equipment, and conditions obtaining in generating stations. In fact the flexibility of modern systems of supervisory control is such that their use is being extended to the control of storm water emergency pumps, release valves, water levels in reservoirs, sewage disposal plant, sluices of irrigation systems and in many other directions.

The types of indicators employed at the control point will, of course, depend upon the nature of the equipment to be supervised. An oil switch for example may be represented by either a rotary semaphore or a combination of red and green lamps, while in the case of transformer tap changing gear a number of lamps may be provided, one for each position of the switch. As previously mentioned, indications may be continuous or obtainable on demand.

With the former arrangement, changes in the position of the remote equipment are automatically shown, while in the case of " on demand " working the position or condition of the plant is indicated back only upon the control engineer bringing the appropriate circuit into operation.

It will be clear that when indications are given on demand, the communication channel may also serve other purposes. It does not follow, however, that continuous indication involves the use of a channel to the exclusion of all other services, since the transmission of signals over the channel is necessary only when changes take place in the condition of the remote equipment.

In order to provide adequate safeguards, a check back feature is usually associated with remote indication as with remote control, each signal received being transmitted back to the initiating point before the corresponding indication is displayed. In this manner false indications are prevented in the event of mutilation of the original signals.

REMOTE METERING.

In the majority of cases, remote metering is combined with remote control and indication and, by means of selective equipment arranged to give any desired order of priority, is often so introduced that all three services may share one or more channels.

Different methods of obtaining remote meter readings are employed and the choice, as previously mentioned, depends to some extent on the channel available. The simplest system consists in merely using pilot wires as extensions of the usual leads between the instrument transformers or shunts and the meters at the indicating point.

This method is quite practicable, but involves the use of very sensitive instruments and errors of a serious nature would be introduced by any considerable variation in line resistance and leakage. Generally speaking it is therefore only applicable over comparatively short distances, and for such work has proved satisfactory in service.

When the line is not suitable for any reason for such direct transmission, a form of repeater is available which transmits over the pilot wires a direct current derived from an independent source and controls the value of this current, making it proportional to the deflection of the originating meter. A device of this kind is suitable for use in conjunction with any line capable of passing direct current but while it eliminates the possibility of errors arising from fluctuations in line resistance, it does not obviate those due to variations in line leakage.

Obviously, when a system of remote metering, as in the case of those mentioned above, depends so largely on the characteristics of the line, it would be preferable not to employ the same channel for any other service. Therefore, in order that remote metering and supervisory control may be combined and operated over one channel, impulse systems have been developed which function, not by quantitive transmission, but by trains of impulses indicative of the deflection of the originating meters.

Two types of impulse systems are available. In one the meter reading to be transmitted controls the frequency and in the other the number of impulses. These are suitable for use over any communication channel and, in the case of the numerical system, can very conveniently be combined with supervisory control, the signals for which are also usually transmitted on a numerical basis.

Readings at the control point may be given

either continuously or on demand, as with remote indication of switch positions and the like, and by employing selective apparatus one channel only can then be made to serve a large number of meters at the distant station or stations according to the requirements of the network. Where continuous readings are so given over one channel, the arrangements are such as to give each originating meter access to the channel as and when changes in deflection occur. Should the channel be engaged when a change takes place, the signal initiated by the meter is repeated automatically until access to the channel is gained and the new reading transmitted to the control point.

(*To be continued*).

Notes on the Rupturing Capacity of Switchgear.

MANY Electricity Supply undertakings are to-day faced with problems arising out of the connection of their systems to the Grid. One of the most difficult of these problems relates to the increased breaking capacity required of switchgear. For cases where it has been determined that the existing switchgear cannot safely be trusted to deal with the new conditions, three main methods have been suggested for meeting the situation, (1) a completely new switchgear system may be installed; (2) the existing system may be modified by fitting oil circuit breakers of larger rated capacity into the existing switchgear and (3) the increase of the breaking capacity of the existing oil circuit breakers by the addition of such devices as explosion pots.

It is obvious that no criticism can be made of the first method—namely, the installation of a new switchgear equipment—on the score of efficiency and safety. This course will, however, involve a fairly heavy capital expenditure. Therefore the second and third methods will receive every possible consideration by those responsible, due to considerations of first cost.

The substitution of oil circuit breakers of larger breaking capacity than those previously in commission seems at first glance to offer a sound solution in those cases where there is sufficient space available to accommodate a breaker of larger capacity. But no greater error could be made than to imagine that the kVA breaking capacity of switchgear is a function which concerns only the oil circuit breaker. Assume, for instance, that a circuit breaker of 75,000 kVA breaking capacity has been substituted for one of 50,000 kVA; there is obviously a proportionate increase in the value of the short circuit current, and it should be borne in mind that the electromagnetic forces set up by short circuits increase according to the square of the current. Thus the insulators, the current transformers, the tying of the strap or bar connections and the tying of the busbars themselves could not reasonably be expected to withstand the increased mechanical forces set up on short circuit. It thus becomes evident that the substitution of a larger circuit breaker is but one item and that to ensure proper safety and efficiency, the rest of the apparatus in the cubicle, truck or other structure, in which the switches are to be installed, must be strong enough to withstand the increased forces which will be imposed.

The third method suggested for meeting the situation, as mentioned above, involves the introduction to the circuit breaker of devices generally known as explosion pots, with a view to increasing its breaking capacity. This method of conversion should never be considered. Explosion pots undoubtedly serve a useful purpose if they form part of the original design of a breaker, but no appreciable increase in the breaking capacity of a complete unit could be effected by fitting explosion pots to existing oil circuit breakers in existing cubicles or trucks. This suggested misuse of explosion pots is to be regretted as it is liable to bring the device into disrepute, whereas the explosion pot properly applied to specially designed oil circuit breakers, is undoubtedly of value.

Great caution should therefore be exercised in approaching questions relating to the increase of the breaking capacity of switchgear equipments, as such economies as might seem to be effected by the saving in initial expenditure may be far outweighed by the results of the subsequent troubles which are liable to occur, unless the whole switchgear and not merely the oil circuit breaker is made suitable for the new conditions.

C. C. GARRARD.

Automatic Control of Mercury Arc Rectifiers.

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In the last issue of the G.E.C. Journal (Vol. IV., No. 2, May, 1933), appeared an article describing the design and construction of the latest type of mercury arc rectifier. It is the general practice to-day to operate this class of gear by "automatic" or "remote" control, both of which have reached a very high standard of reliability.

The author of the present article discusses the methods available of controlling mercury arc rectifiers by automatic or remote means.

THE mercury arc rectifier is admirably suited for automatic or remote control, manually operated equipment of this type seldom being found in practice.

Reference has been made (*G.E.C. Journal*, Vol. IV., No. 2—"The Mercury Arc Rectifier," by A. T. Bartlett) to the applications of mercury arc rectifiers, but as A.C. distribution is being widely adopted for industrial power and domestic supply networks, it is proposed in this article to deal more particularly with traction distribution systems and subsequently to outline the main differences in control gear for rectifiers working in a three-wire lighting and power network.

In describing the automatic control of electrical equipment, some confusion is apt to arise in the actual meaning of the terms "automatic control" and "remote or supervisory control." It has therefore been considered necessary to begin by defining what each phrase is intended to convey.

Automatic Control.—By "automatic control" of an electrical equipment, such as that installed in most sub-stations, is meant the self-adjustment of the equipment, without the intervention of any human agency, to meet varying conditions of load. A better term, and one which it is proposed to adopt in this article is "self control." The term "automatic" is reserved for reference to routine operations which are effected without human agency in both remote and self-controlled equipments.

Remote or Supervisory Control.—In remote control the automatic features of the equipment are still retained but they are initiated by human agency from a distant central control point.

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Fig. 1.—Control switchboard at the Alperton substation of the London Electric Railway Co., for controlling six mercury arc rectifier sub-stations, two of which will be completed in the future.

CHOICE OF CONTROL FOR TYPICAL TRACTION SYSTEM.

In preparing a suitable control scheme for a traction system, the power for which is to be taken from a number of rectifiers, it is necessary first to decide which form of control is to be adopted, *i.e.* (*a*) self-control or (*b*) remote control.

Self-control of machines by load conditions on the network is not very satisfactory for traction service because of the violent load fluctuations experienced. For instance if a train approached a substation which was shut down, the load demand would not operate the substation starting relay until the train was fairly close to the substation. The plant would probably be connected to the network only when the train was level with the substation and the load would fall away rapidly as the train

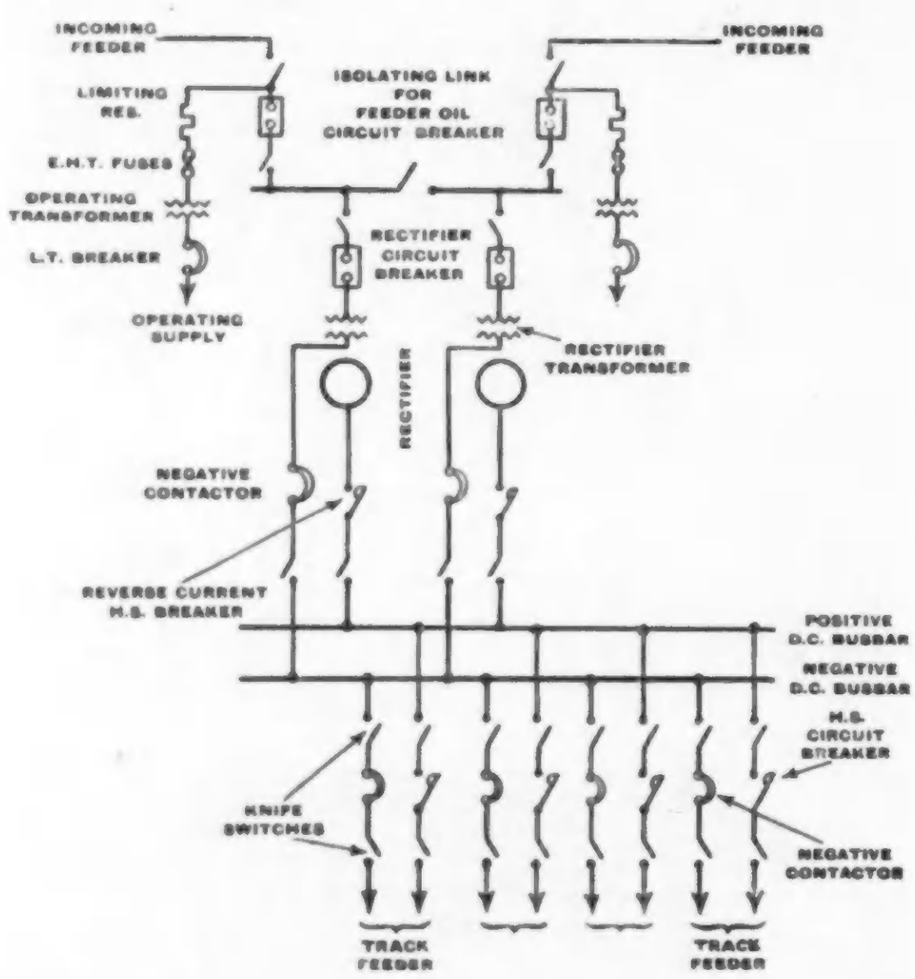


Fig. 2.—Diagrammatic layout of typical mercury arc rectifier substation.

moved away. Time switch control would enable the demand to be forestalled, but such apparatus does not respond to emergency conditions which may arise due to fog or holiday traffic. It is therefore assumed that the typical scheme under consideration will be remote controlled.

Remote control may be accomplished either by (1) pilot wire control, if the distance from the control point to the substations is short—say not more than 5 or 6 miles; (2) selective supervisory control if the distance from the control point to the substations is relatively great; or (3) high frequency carrier current system transmitted along the track.

Control by pilot wire is very simple but entails the use of a large number of pilot wires, whereas the supervisory control system uses very few pilot wires but is more complicated, as selective control equipment must be provided both at the control point and at each substation. The carrier current system requires no pilot wires whatever but necessitates a considerable amount of auxiliary equipment.

Fig. 1 shows the control board at the Alperton substation of the L.E.R. for controlling by pilot wire six substations on the track.

Further elaboration of the various types of remote control available are not discussed here, as they are being fully dealt with in a series of articles entitled "Communication, Protection and Supervisory Control Systems for Electric Power Networks," the first of which appears on page 165; but it should be mentioned that all these systems have been developed to a very high degree of reliability, and the choice of type depends almost entirely on the relative cost of the large pilot cable in the first case, of the small pilot cable together with the supervisory control apparatus in the second case, and of the auxiliary equipment mentioned in the last case.

Whichever system of remote control is adopted, the services required of it will generally be as follows:

(*a*) To close any E.H.T. feeder.
(*b*) To open any E.H.T. feeder.
(*c*) To start any rectifier and parallel on to the D.C. network.
(*d*) To shut down any rectifier.
(*e*) To close any track feeder.
(*f*) To open any track feeder.
(*g*) To indicate the position of all important switches on the system.
(*h*) To give facilities for reading the track voltage at any substation.
(*k*) To give facilities for reading the load on any rectifier.
(*l*) To give facilities for controlling track paralleling circuit breakers at various points on the system.

In many cases some or all of the following auxiliary services can also be controlled conveniently from the central point:—

(*a*) Opening and closing E.H.T. & L.T. circuit breakers for track signalling supplies.
(*b*) Opening and closing E.H.T. and L.T. circuit breakers for passenger station, siding and tunnel lighting supplies.
(*c*) Controlling compressors for giving a compressed air service for points, signals, etc.

Assuming that a choice has been made of remote control, the automatic control gear in the substation can be considered. The layout of a typical mercury arc rectifier substation is shown diagrammatically in fig. 2.

MAIN SWITCHGEAR.

The E.H.T. switchgear in each substation is normally of standard design (figs. 3 and 4), details depending upon the layout of the E.H.T. distribution system. Usually there are two incoming feeders which may form a link in a ring main system, or they may be parallel feeders. In either case the protective scheme would follow well established lines and would be designed to suit the general layout of the E.H.T. distribution system.

Supplies for any auxiliary services may be taken from the E.H.T. busbars in the usual manner and the supply for the rectifier through the rectifier oil circuit breaker. Up to this point all apparatus follows standard practice but special attention must be paid to the rectifier oil circuit breaker. On rare occasions rectifiers lose their valve action and suffer what is generally known as a "back-fire." In effect this is a dead short circuit on the L.T. side of the rectifier transformer. Since the transformer reactance is low and the rectifier reactance negligible, a very severe disturbance is experienced on the E.H.T. system. When the E.H.T. circuit is being ruptured a further effect becomes apparent and seems to be peculiar to rectifier circuits. The exact nature of this effect is not yet fully understood, but it has been found necessary to provide rectifiers with oil circuit breakers which have a larger rupturing capacity than would normally be necessary.

To minimise the disturbance caused by these rare "back-fires," each rectifier circuit breaker should also be fitted with a quick acting overload tripping device which should be set to operate at not less than 5 times full load. With this arrangement momentary overloads caused by track short circuits or other disturbances external to the rectifier will not cause undesired shut-downs, but overload protection of not less than five times full load is hardly sufficient for normal working conditions. The equipment should therefore also be protected by standard inverse time limit overload and earth leakage relays.

The E.H.T. supply is connected directly from the oil circuit breaker to the rectifier transformer (fig. 2). The neutral point of the main transformer L.T. windings is the negative pole of the rectified supply, and in the case of an earthed rail return may be connected to the negative busbar through an isolating

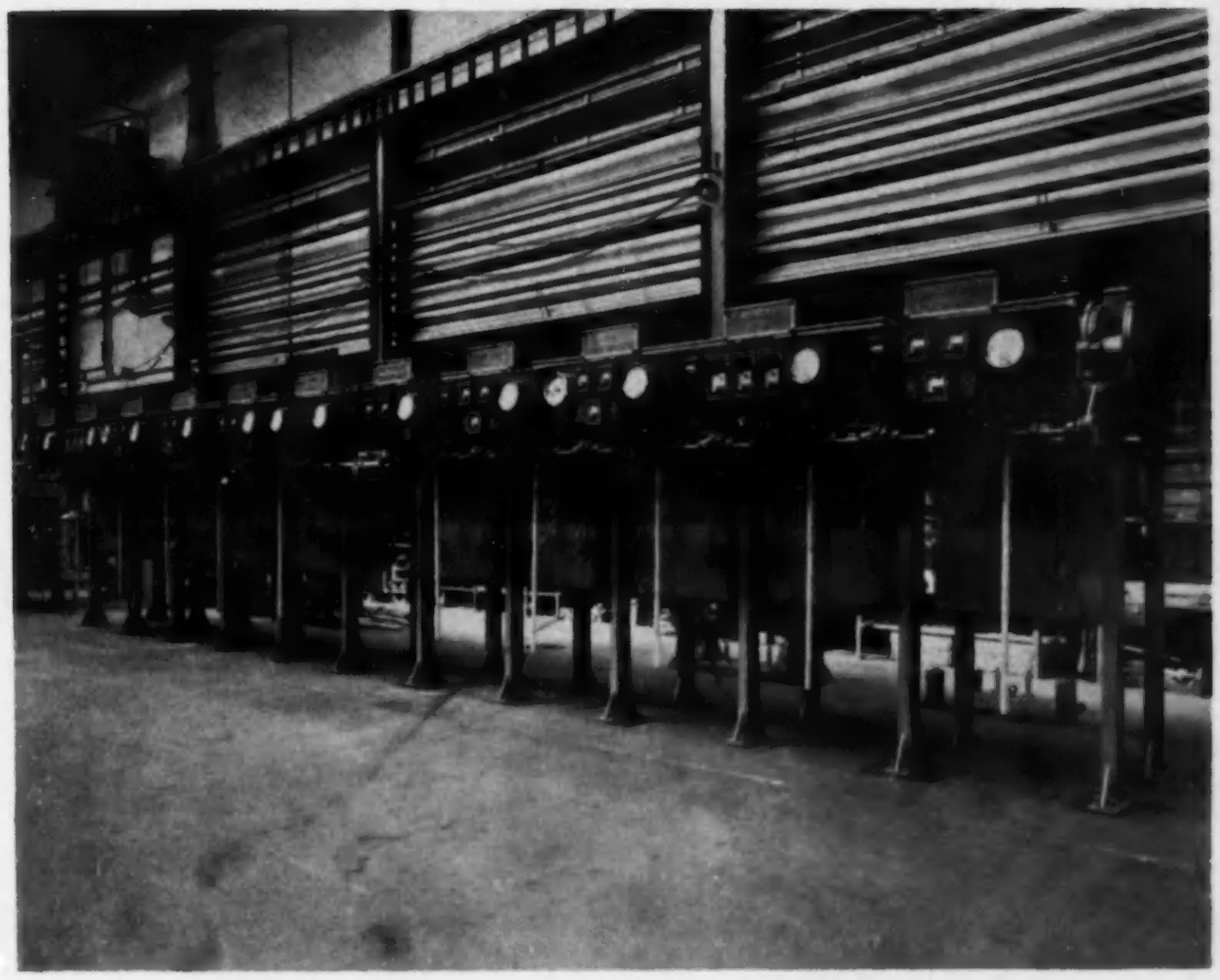


Fig. 3.—Typical E.H.T. metalclad switchboard.

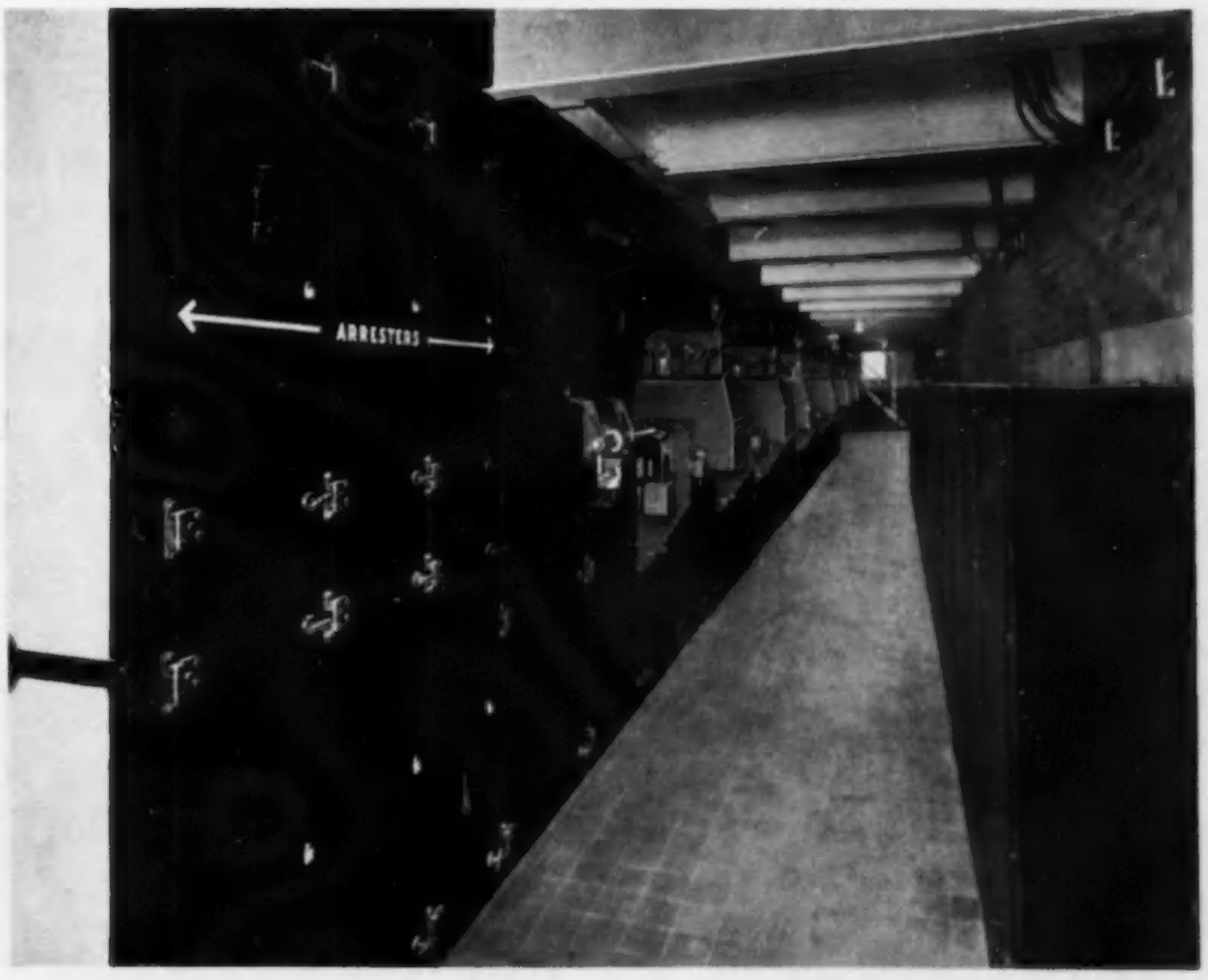


Fig. 4.—Typical stonework cubicle switchboard controlling 11,000 volt circuits.

switch. If the return is by insulated conductor, an electrically operated contactor (fig. 5) and manually operated isolating switch will form the link between the transformer neutral and the negative busbar.

Fig. 5.—Group of direct current negative contactors for rectifiers and track feeders.

The phase connections of the main transformer L.T. windings (usually 6 or 12) are connected direct to the rectifier main anodes. From these points the circuit is through the rectifier tank to the cathode, which forms the positive pole of the rectifier equipment. The switchgear required on the positive pole is a reverse current high speed circuit breaker and isolating switch. The high speed circuit breaker normally operates as a switch on the D.C. side of the rectifier, but the need for its special design arises due to the necessity for meeting the conditions caused by "back-fires." If one or more anodes lose their valve action, not only do all healthy anodes feed into the faulty ones, but if the machine is connected to a D.C. network fed from other sources the cathode also supplies a heavy reverse current to the faulty anodes. This circuit can only be broken from the D.C. side of the rectifier and to prevent damage to the rectifier a very rapid opening of the D.C. circuit is advisable. It must also be borne in mind that the quicker this circuit is opened, the less will be the disturbance on the D.C. system. To meet these conditions the reverse current high speed circuit breaker (figs. 6 and 7) has been developed which is capable of rupturing the circuit in approximately $\frac{1}{100}$ sec.

Nearly all high speed circuit breakers operate by the reaction of two magnetic fields and are polarised instruments, functioning only when a heavy current flows in one direction. It will therefore be seen that the reverse current high speed circuit breaker does not give any protection against overload currents in the normal direction. Such conditions, however, need not be catered for as sufficient protection is afforded by the overload protective devices on the E.H.T. oil circuit breaker. The D.C. track feeders are fitted with high speed circuit breakers, arranged to trip on excessive overloads in the forward direction. In this case the polarised feature of high speed circuit breakers is employed to secure isolation of a faulty feeder only. By referring to fig. 8 it will be seen that if a fault should occur at "A," breakers "B" and "C" only would trip. Breakers "E" would pass a reverse current and breakers "F" would have the forward fault current divided between them in varying proportions, so that none of them would be tripped.

AUXILIARY APPARATUS.

The control of certain auxiliary apparatus essential to a mercury arc

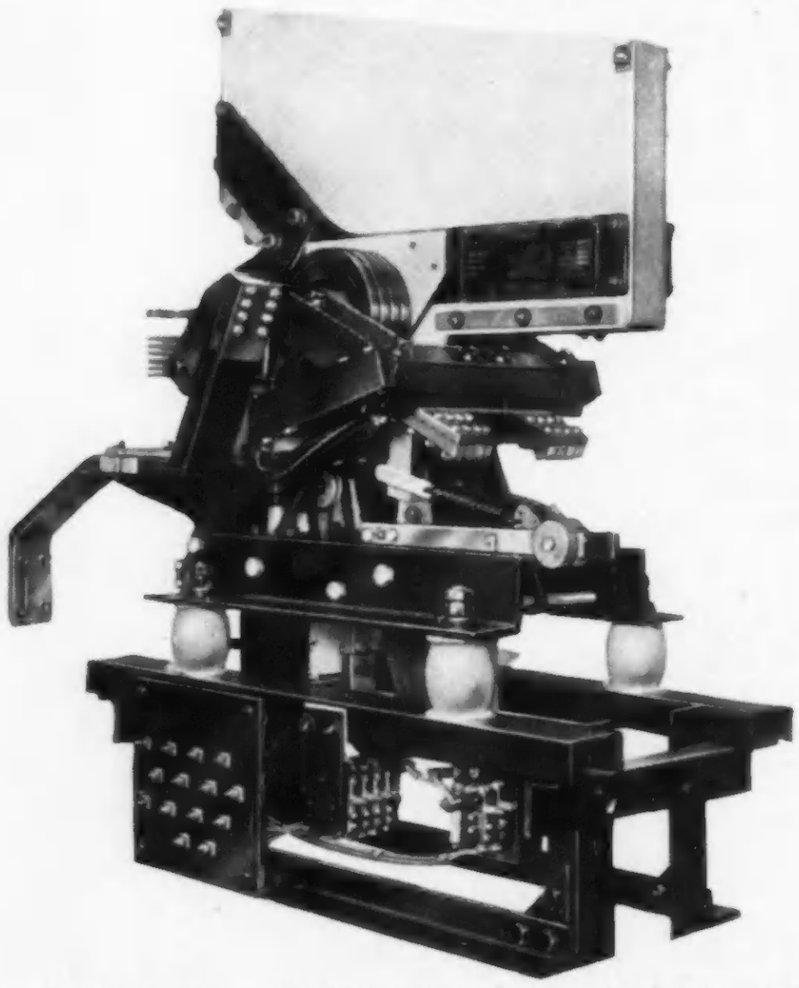


Fig. 6.—Near view of G.E.C. high speed circuit breaker.

rectifier is most important, since the failure of any item would probably cause the rectifier to be put out of service.

The auxiliary apparatus may be divided into the following sections :—

(*a*) Vacuum pumps.
(*b*) Cooling equipment.
(*c*) Starting or ignition apparatus.
(*d*) Auxiliary anodes.

VACUUM PUMPS.

Diffusion Pump.—The diffusion pump maintains the very high degree of vacuum necessary in the tank and works on a principle similar to that of the steam ejector. Mercury is boiled by a small heater, the vapour being passed through nozzles where it picks up air and gases from the rectifier tank. The mixture of mercury vapour and air is then passed into a condensing chamber where the mercury is condensed and is separated from the air. The mercury returns to the boiling chamber and the air is exhausted to the next stage. It is found advisable to run the diffusion pump continuously, even when the rectifier is shut down.

The switchgear for controlling the supply to the heater is very simple but certain precautions must be taken. The diffusion pump is usually mechanically connected to the rectifier tank and is therefore at a potential approximately equal to that of the positive busbar of the D.C. system. Further, for the correct working of the rectifier, it is most important that the tank is never earthed. It is therefore usual to supply the diffusion pump heater from the operating supply through an insulating transformer.

The diffusion pump heater is connected so that it is always in service when the operating supply for the unit is alive. Means must be provided, however, to switch out this heater in the event of failure of the cooling water supply to the condensing chamber. To accomplish this the diffusion pump heater is fed through a contactor which only closes when a water flow relay in the circuit of the cooling water indicates that the cooling apparatus is operating correctly.

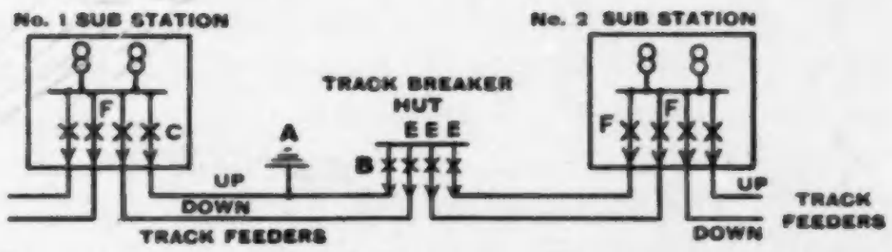


Fig. 8.—Arrangement of high speed circuit breakers on track feeders.

Backing Pump.—The diffusion pump cannot operate over a very wide range of pressure, so that some means must be adopted to maintain the diffusion pump exhaust at an absolute pressure of a few millimetres of mercury. This is accomplished by a rotary oil-filled pump, driven by a small motor.

Fig. 7.—Bank of 3000 and 4000 ampere high speed circuit breakers controlling mercury arc rectifier and track feeder circuits.

There are several ways of arranging the vacuum system between the diffusion pump exhaust and atmosphere, while the control gear required for the backing pump must be varied to suit the arrangement adopted. The best arrangement of the vacuum equipment from many points of view, is to discharge the vapour from the diffusion pump into an interstage reservoir, a small chamber which is periodically evacuated by the backing pump. A contact-making pressure gauge is fitted to this reservoir which starts and stops the rotary pump as and when required. The great advantage of this scheme is that the rotary pump runs only for 10 to 15 minutes once in every 24 hours.

Between the interstage reservoir and the backing pump a thoroughly reliable valve must be fitted, and one of the best forms is that known as a barometric valve. This valve consists of a tube about 36 ins. long, the upper end of which is connected to the interstage reservoir, while the lower end dips slightly below the mercury level in a chamber which is exhausted by the rotary pump. When the pump is in operation air from the interstage reservoir passes down the barometric tube and bubbles through the mercury in the lower chamber. When the pump stops and the pressure in the lower chamber rises, the mercury runs up the tube to approximately barometric height thus making a very effective and absolutely leak-proof valve.

The disadvantages of the above scheme is that after a failure of the E.H.T. supply for more than about 10 minutes, the diffusion pump ceases to operate and the interstage reservoir feeds back into the rectifier tank. This locks the rectifier out of service until the diffusion pump has time to heat up again and evacuate the rectifier.

This trouble may be overcome in a number of ways, of which the best is to introduce a second barometric valve between the diffusion pump and the interstage reservoir. If now a failure of the supply allows the diffusion pump to cool and cease operation, the interstage reservoir cannot feed back into the rectifier. As soon as the E.H.T. supply has been restored the rectifier vacuum will usually be good enough to allow the plant to be operated until the diffusion pump comes once again into operation.

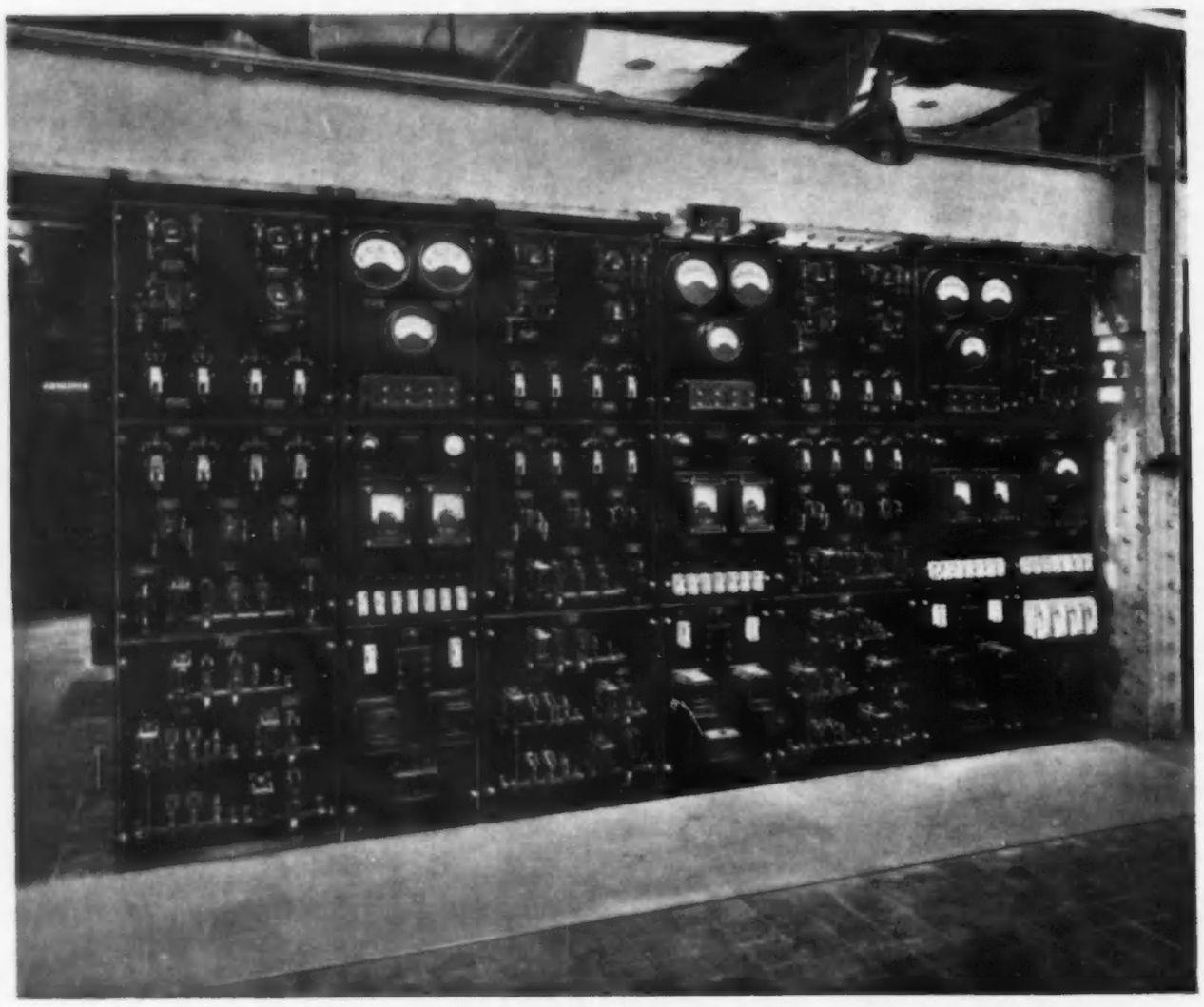


Fig. 9.—Relay panel for the automatic control of three mercury arc rectifiers.

Cooling Equipment.—Some form of cooling apparatus is required for maintaining a moderate and steady temperature of the anodes, cathode and rectifier tank; also as indicated above, the condensing chamber on the diffusion pump must be kept as cool as possible. These two cooling systems are largely independent of each other and will be treated separately. There are a number of systems which may be adopted depending upon local conditions. The simplest scheme and one which entails a minimum of apparatus in the substation is to make use of a public water supply. For such a scheme to be economical there must, however, be a plentiful supply of water at a low rate. The diffusion pump uses only about 9 gallons per hour but the main cooling system uses approximately 0.2 gallons per hour per amp. of D.C. output. This figure is only very approximate and depends to some extent on the load factor, size of rectifier, voltage of D.C. system, also on the ambient temperature. If this system of cooling is adopted the diffusion pump cooling system will be controlled by a hand operated valve and will be continuously in service. The main cooling system is controlled first by an electrically operated valve which opens only when the rectifier is in operation, and secondly by a thermostatically controlled valve designed to regulate the flow of water to maintain a constant temperature of the water leaving the rectifier jacket. This type of control economises as far as is possible the quantity of water used and also maintains the rectifier at the best operating temperature.

Very frequently a plentiful water supply is not available. In such cases it is necessary to adopt a closed cooling system. Water is circulated through the rectifier jacket and a recooler by a pump. The recooler usually consists of a nest of pipes on to which a stream of air is directed by a fan. A small make up tank is also provided to ensure that the water system is kept full. In order to economise in the power consumed by the auxiliaries, arrangements can be made to shut down the fan during light loads and rely only on natural radiation from the cooler. To maintain the rectifier at proper working temperature the thermostatically controlled valve is still installed, but in this case it bypasses the surplus delivery from the pump through the cooler only.

The main cooling system operates only when the rectifier is on load, but the diffusion pump must be operated and supplied with cooling water at all times. It is therefore obvious that some special arrangement must be made. Several schemes are available. One which meets with general approval consists of supplying this pump from the public water supply. As the water consumption is so low this is usually possible, and the waste water can conveniently be used to keep full the small make-up tank for the main cooling system. This arrangement is, however, not always possible and it may be advisable to install a small closed cooling system complete with pump, fan and cooler for use in conjunction with the diffusion pump. Another method is to circulate water through the diffusion pump and a comparatively large tank, fitted with radiators or cooling fins, the tank being so designed that sufficient heat is dissipated from its surface.

It will be realised that the description given above covers but a few of the more common methods of recooling in use. Others are adopted in special cases where peculiar local conditions may render them more convenient.

It has already been mentioned that the rectifier tank is not at earth potential, while the cathode which is also water cooled is at the potential of the positive D.C. busbar. It is therefore evident that precautions must be taken in the cooling system to maintain the tank insulated from earth, and also to maintain the insulation between the tank and the cathode. It is well known that pure water is quite a good insulator and in practice it is found possible to insulate the supply pipe-work from the rectifier sufficiently by inserting a length of rubber hose in the water system where necessary. The length of hose required depends partly on the quality of water available and partly on the cross section of the water column necessary to carry the required flow. A satisfactory length of hose is usually about 10 feet. Where a closed water system is used, the water system, including cooler, pump, make-up tank, etc., is completely insulated from earth, but rubber connections are still necessary to maintain the insulation between the cathode and rectifier tank.

Little has been said regarding the cooling of the anode stems, which is practically always carried out by means of self contained radiators. In the G.E.C. design of anode seal, these take the form of simple cast iron fins slipped over the anode stem. With many other designs of anode, rather more elaborate cooling is necessary and the radiators take the form of a small tank fitted with fins, the tanks from time to time being filled with water when the rectifier equipment is shut down for inspection and maintenance.

AUXILIARY ANODES.

The modern rectifier is fitted with two or more auxiliary anodes designed to maintain a hot spot on the cathode during extremely light loads and at times when the main D.C. circuit is not complete. These anodes operate from an insulating transformer and the output is controlled by means of choke coils and resistances between the cathode and the mid point of the insulating transtormer. The insulating transformer primary may be energised from the main transformer secondary or from an auxiliary operating supply according to which method is the more convenient. The auxiliary anodes are usually left in operation during the whole time the rectifier is in service.

IGNITION APPARATUS.

Some means is necessary to start the emission of electrons from the cold cathode. This usually takes the form of a magnetically operated ignition anode, which may be dipped into the cathode pool for a moment and withdrawn again. Before operating the ignition anode a potential is applied between this point and the cathode, and as the electrode is withdrawn from the mercury pool an arc is formed which produces the necessary hot spot on the cathode and causes electronic emission. If the auxiliary and main anodes have previously been energised current immediately flows in their respective circuits, the cathode is maintained in an active state and the ignition circuit can be disconnected. The supply for the ignition circuit may be either D.C. or A.C. but a D.C. supply is in many ways more satisfactory.

Fig. 10.—Relay panels for the self-control of a mercury arc rectifier.

The supply may be obtained from a small motor-generator set or a small metal-oxide rectifier and is usually about 100 volts D.C. The current in the ignition circuit is limited to about 5 amps. by a suitable resistance.

CONTROL SUPPLIES.

To operate the various auxiliaries and to energise the various control and protective circuits a source of low voltage supply is necessary.

There are a number of sources, one or more of which can usually be made available. These are as follows :—

(*a*) Secondary battery.
(*b*) Auxiliary transformer.
(*c*) D.C. network.
(*d*) A.C. supply from L.T. side of rectifier transformer.
(*e*) D.C. supply from the rectifier.

All these sources of supply have certain advantages and limitations and several are usually employed on any one plant, different combinations being chosen in various cases to meet the existing local conditions.

(*a*) A secondary battery is very convenient in that it is almost entirely independent of the main supply, but it is expensive and maintenance charges are relatively high. Further, a number of the auxiliaries supplied must be carefully insulated from the main network and since insulating transformers are not possible with a D.C. supply, a motor generator set or other inconvenient insulating device, becomes necessary.

For these reasons this form of auxiliary supply is not used to any extent. It is however, common practice to provide a small battery for tripping the most important circuit breakers.

(*b*) An auxiliary transformer energised from the E.H.T. busbars or the live side of the incoming feeders is usually the most convenient source of operating supply. Such a transformer (about 10 kVA) may be connected on the E.H.T. side through isolating links limiting resistances and E.H.T. fuses (see fig. 2). The L.T. supply is protected either by fuses or a small circuit breaker with time lag overload attachment.

The operating supply from a transformer of this nature is available whenever the E.H.T. supply to the substation is alive and can therefore be used for closing the E.H.T. breakers, operating diffusion pump, etc.

The chief disadvantages in this scheme is that a relatively small transformer is connected to the E.H.T. distribution system, but this disadvantage is countered by paying special attention to the insulation and construction of the transformer. This source of auxiliary supply becomes expensive and unsatisfactory if the E.H.T. system operates at a pressure above approximately 33 kV.

(*c*) The D.C. Network, is seldom very convenient for the main source of operating supply, the chief disadvantage being that, for this supply to be available before starting up a rectifier, the system must be fed from another source. Occasionally, if the plant is purely a boosting station, this source can conveniently be used.

(*d*) The A.C. supply from the L.T. side of the main rectifier transformer is frequently used for exciting the auxiliary anodes and operating the ignition gear, etc. The disadvantage of this source is that it only becomes available when the E.H.T. oil circuit breaker has been closed.

(*e*) The D.C. supply from the rectifier only becomes available after the ignition is complete, but this source is frequently used for closing the D.C. breakers and exciting the high speed circuit breaker hold on coil. If the D.C. system operates at 1500 volts or 3000 volts, this source is not very satisfactory as control wiring operating at such high voltages is not advisable.

It should only be repeated that in general several of the above sources of operating supply should be in any particular station, the various operations used being divided among them. In every case peculiar local conditions must be studied and the most economical sources of supply adopted.

VOLTAGE CONTROL.

In the case of either a rotary converter or a motor converter of suitable design, the D.C. output voltage can readily be controlled by varying the resistance in series with the shunt field. Unfortunately no easy means has so far been developed for use with mercury arc rectifier plants.

A number of methods are however, available :

(*a*) *Off load tapping switch on main transformer.*

As the sub-heading implies, the tapping switch cannot be operated under load and can therefore only be used for making semi-permanent changes in the transformer ratio.

For traction work this method is quite satisfactory and is almost universally adopted.

(*b*) *On load tapping switch on main transformer.*

This equipment is designed for operation under load and may be operated electrically or manually as desired. An electrical equipment is of course suitable for remote control or automatic control.

(*c*) *Induction regulator.*

An induction regulator connected into the main transformer E.H.T. circuit can be arranged to buck or boost the L.T. A.C. pressure and so vary the D.C. pressure.

Again the induction regulator may be manually or electrically controlled and in the latter case operated from a remote control point or automatically by a D.C. voltage regulating relay.

The great advantage of an induction regulator is that it gives continuous variation throughout its whole range, while the on load tapping switch must necessarily move in steps.

(*d*) *Saturation of Interphase Reactor.*
A fourth method which can be used if the transformer connection is such that the equipment includes an interphase reactor, is to fit a shunt winding to the interphase reactor and to modify the saturation of the iron circuit in the interphase reactor by varying the shunt excitation.

Finally, voltage control may be effected by separately exciting the grids in front of the anodes. The possibilities and limitations of "grid control" have been dealt with in previous articles in this journal ("Gasfilled Relays," Vol. III., Nos. 2 and 3), and this point will therefore not be dealt with here in detail.

TYPICAL EQUIPMENT FOR LIGHTING AND POWER DISTRIBUTION.

Having dealt in detail with a traction equipment it will be sufficient to mention the main differences in control gear for a rectifier operating on a three wire lighting and power network.

As the rectifier is essentially a two-wire machine, the first problem which arises is the method for dealing with any out of balance current on a three wire network. There are two main courses open. These are as follows :—

(*a*) Two rectifiers may be operated in series, one from positive to midwire and the other from midwire to negative. This system is adopted largely on small units but suffers from an inherently low efficiency. By far the greatest loss in a rectifier equipment is that which is due to the arc drop. If two rectifiers are connected in series the arc drop is doubled and the efficiency of the combination correspondingly lowered.

(*b*) The other alternative is to use one rectifier connected across the outers and operating in conjunction with a rotating balancer. This system is usually adopted for larger units and arrangements are made for the balancer to be run up and placed in operation before allowing the rectifier to be connected to the D.C. system.

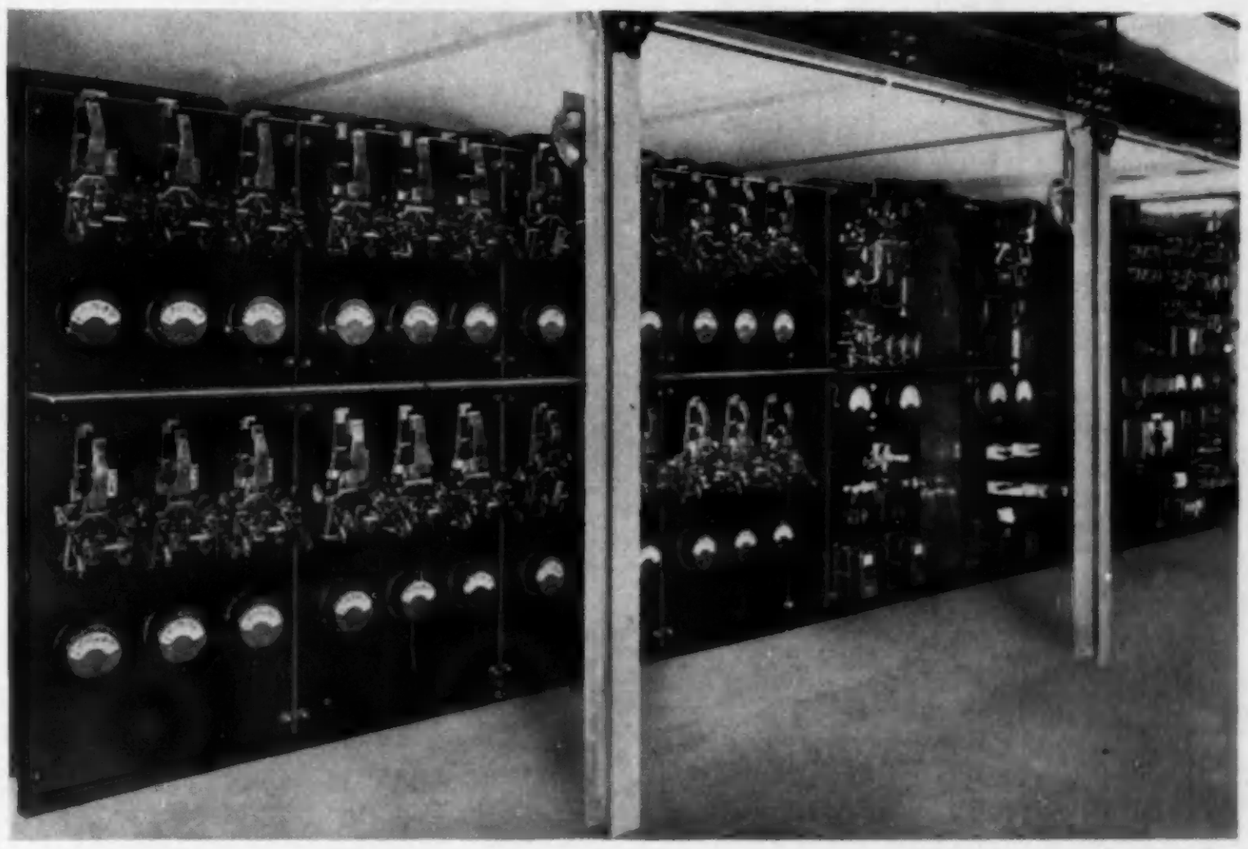


Fig. 11.—500 volt D.C. feeder switchboard with rectifier and balancer control panels on right hand side.

The second consideration is that the voltage of a power and lighting system must be maintained constant at the consumers premises. This condition is fulfilled by providing means for varying the D.C. voltage and controlling the busbar voltage by a voltage regulating relay, which may be compounded if desired to compensate for feeder drop.

Finally the machines must parallel smoothly on to the network to prevent any sudden voltage variations which may cause lights to flicker. This can easily be accomplished with a rectifier by making use of the fact that the plant cannot normally operate reversed. The voltage regulating equipment is operated after shutting down to reduce the D.C. voltage to a minimum. This means that the rectifier will in general parallel on to the D.C. network at a voltage below that of the busbars. The voltage is then gradually raised to the correct value and the rectifier gradually picks up its load.

RELAYS.

A rectifier plant is comparatively simple and few relays are required; they may, however, be divided into two classes.

1. *Operating Relays.*
   - (*a*) Low voltage starting relay.
   - (*b*) Voltage regulating relay.
   - (*c*) Overload starting relay.
   - (*d*) Underload shutting down relay.
   - (*e*) Loading resistance relay.
   - (*f*) Time delay relay.
   - (*g*) Control thermostats.
2. *Protective Relays.*
   - (*a*) E.H.T. overload and earth leakage.
   - (*b*) Water flow relays.
   - (*c*) Vacuum relays.
   - (*d*) Stalling relay.
   - (*e*) Lock out relay.
   - (*f*) Protective thermostats.

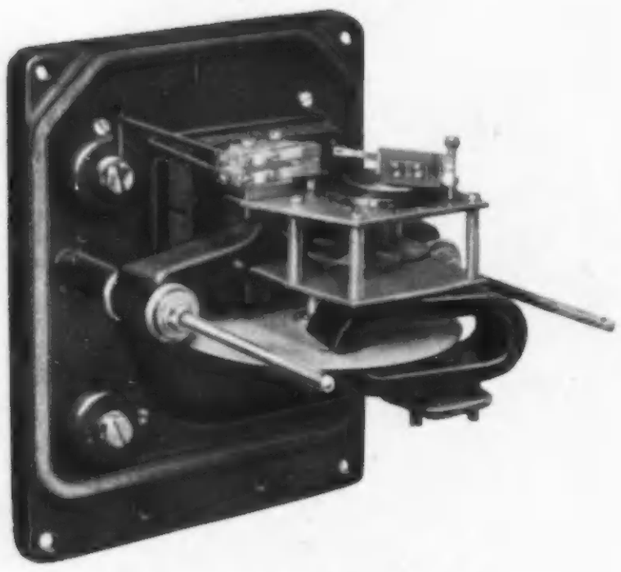


Fig. 12.—Stalling relay.

Various manufacturers have developed quite different types of relay for carrying out most of the above functions but space only permits of a short description of one of each type.

OPERATING RELAYS.

Voltage Regulating Relay.—Control is effected by a balanced beam controlled by a solenoid. When the voltage to be regulated is correct, the beam floats between a pair of contacts. If the voltage departs from normal the excitation of the solenoid is varied and the balance of the beam is upset. The beam topples one way or the other according to circumstances and contacts are closed which initiate operation of the voltage regulating gear. To obtain good contact pressures and quick break action the beam system is carefully designed to give a definite topple motion to and from the floating position. The sensitivity of the relay is approximately $\pm$ 1½ per cent.

The Low Voltage Starting Relay.—This relay is similar in design but the contacts are arranged to operate only when the voltage is low.

A wide range of settings is obtained by varying a resistance in series with the operating coil.

Overload Starting and Underload Shutting Down Relays.—The function of these relays is to start up or shut down rectifiers in a multi-unit station according to the demand on the station. A novel design of relay for both the above which enables robust construction and extreme sensitivity to be combined, operates on the same principle as a moving coil ammeter but in this case the coil is fixed and the permanent magnet system moves. The fixed coil is wound in two sections on to a soft iron ring in such a manner that consequent poles are produced 180° apart. The coils are energised from a shunt and with this type of construction can be designed to pass a relatively large current and so ensure large operating forces. The only moving part is a large permanent magnet which may be built up of several laminations. The magnet is pivoted in the centre of the iron ring and its movement in the magnetic field is made to operate contacts. The design of the contacts can, of course, be varied to suit particular requirements.

Loading Resistance Relay.—With some forms of transformer connection the voltage-load characteristic of a mercury arc rectifier shows a sudden and sharp rise of voltage at extremely light loads. In order to overcome this difficulty a loading resistance is connected across the rectifier output terminals. The resistance is designed to impose sufficient load on the rectifier to prevent the above mentioned over-potential. When the external load rises above the critical transitional load it is obviously wasteful to leave the loading resistance in circuit; it is therefore switched out when not required.

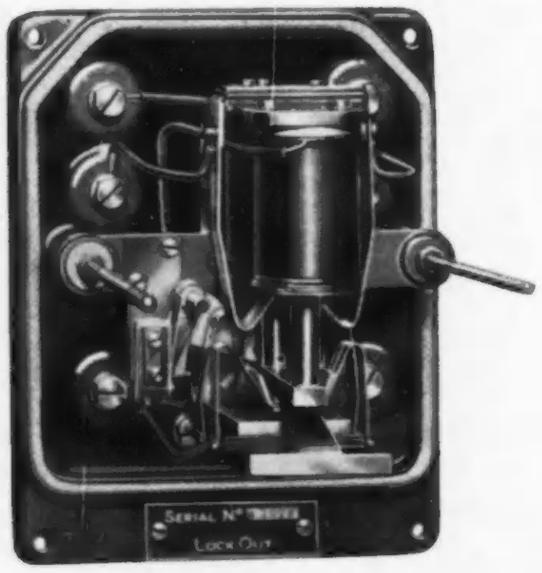


Fig. 13.—Lock out relay.

The loading resistance relay is designed to control this operation. The relay is mounted in one of the main leads from the rectifier and relies for its action upon the field produced by the main current flowing in this bar. The flux is increased by partly surrounding the bar by a fixed soft iron circuit, and completing this iron circuit by a soft iron armature mounted on pivots. By suitably shaping the armature

and controlling its motion by a spring, it can be arranged to operate contacts as required.

Time Delay Relays.—Time delay relays are used for a large variety of purposes and are made to depend for their operation on many different principles. One type operates on the principle of the induction motor (fig. 12). The rotor in this case is a thin disc of aluminium or copper revolving between the poles of an electro magnet and a flat keeper. A rotating field is produced in the magnet system by means of a shaded pole. A contact and spiral spring are geared to the rotor so that when the coil is energised the rotor revolves, winds up the spring and moves the contact so that the circuit is completed after a time delay. When the coil is de-energised the spring returns the contact to its off stop, the speed of the return being controlled by a permanent magnet brake on the disc.

Control Thermostats.—Thermostats are used for controlling the operation of the fan in a closed cooling circuit. One successful design of thermostat operates by the pressure produced by heating certain fluids in an enclosed chamber. The fluid expands a flexible bellows and the motion operates suitable contacts.

PROTECTIVE RELAYS.

E.H.T. Overload and Earth Leakage Relays.—The type usually used is the well-known inverse time limit induction type instrument and no detailed description need be given.

Water Flow Relays.—Water flow relays may be divided into two distinct types, depending on the design of the water circuit. If the warm water is run to waste there will be a break in the circulating water system which enables a very simple type of "bucket" relay to be used. The movement consists of a beam on which are mounted a bucket with an adjustable outlet at the bottom and a counter balance weight. The water discharges into the bucket which when full of water overpowers the balance weight, tips the beam and so operates suitable contacts. Should the flow cease the bucket empties, and the beam and contacts reset.

Such a relay is unsuitable if there is no break in the water circuit as is frequently the case when a closed water system is adopted. In such cases a pressure operated relay may be used, and is fitted into the pipe system at a point where the establishment of a flow of water will alter the pressure in the pipe.

Vacuum Relays.—For automatic working it is necessary to have a means of cutting out the rectifier if the vacuum falls during operation, or of preventing the rectifier being started up with a poor vacuum.

The operation of the Pirani vacuum gauge was described on page 104 of the May issue of the *G.E.C. Journal* (Vol. IV. No. 2).

The vacuum relay is simply a moving coil milliammeter relay connected in parallel with the vacuum indicating instrument. The instrument and relay must be constructed and calibrated to work in parallel across the Pirani gauge.

The most interesting part of this apparatus is the equipment for supplying the constant potential necessary for operating the Pirani gauge.

The simplest source would be a trickle charged secondary cell (only approximately 2 volts is required) but this arrangement is not very satisfactory, as it is difficult to maintain and does not generally give a sufficiently constant potential. A very satisfactory piece of apparatus has, however, been developed which is operated from the A.C. operating supply. The equipment consists of a specially designed transformer, a small metal oxide rectifier and a small smoothing choke. The transformer is designed to give a constant secondary potential on a constant load, with a widely varying primary potential. The rectifier and smoothing equipment

Fig. 14.—Top plate thermostat.

simply convert the low voltage A.C. supply into D.C. for use on the vacuum gauge circuits. The equipment is designed so that a 20 per cent variation in the operating potential causes less than ¼ per cent variation in the D.C. potential to the gauge.

Stalling Relay.—The function of the stalling relay is to measure the time taken by the starting sequence and if due to any fault this time is unduly long, the relay operates to lock-out the equipment until the plant has been inspected. The relay (fig. 12) is actually a time delay relay exactly as described under Operating Relays, section (*f*). The relay is started when the starting impulse is received and stopped when the starting sequence is completed. Normally the time taken by this operation is insufficient to allow the relay contacts to close and the relay simply resets.

Lock Out Relay.—Should certain faults of a serious nature occur, it is inadvisable to allow the

plant to start up automatically until it has been inspected. There are, fortunately very few faults which are likely to occur on a rectifier plant which necessitates a "lock-out."

While several successive heavy overloads will do no harm to equipment it is not advisable to allow the plant to close continually on to a short circuit. Arrangements are therefore made to "lock-out" after several successive heavy overloads.

An overload trip on one of the auxiliary motor circuits such as the water pump or fan motors will probably mean that a bearing has seized or a motor winding has failed and an immediate "lock-out" is advisable.

Similarly the operation of the transformer earth leakage relay will probably indicate a fault which should be investigated.

One form of lock out relay is a very simple instrument (fig. 13); the mechanism consists of a fixed double solenoid which attracts a moving U-piece of iron, on which one or more contacts are mounted as required. When the coil is de-energised the U-piece falls to the bottom position and the moving contacts bridge the bottom fixed contacts. When the coil is energised the armature is sucked up into the coil, the bottom contacts are broken and the top contacts are made. Arrangements are made to latch the armature in the energised position until the mechanism is reset by hand.

Protective Thermostats.—The effect of a prolonged overload on a rectifier is to raise the temperature of the tank and top plate above a safe working temperature. This condition is therefore guarded against by fitting a thermostat to the top plate (fig. 14) which will shut the plant down if an excessive temperature is reached.

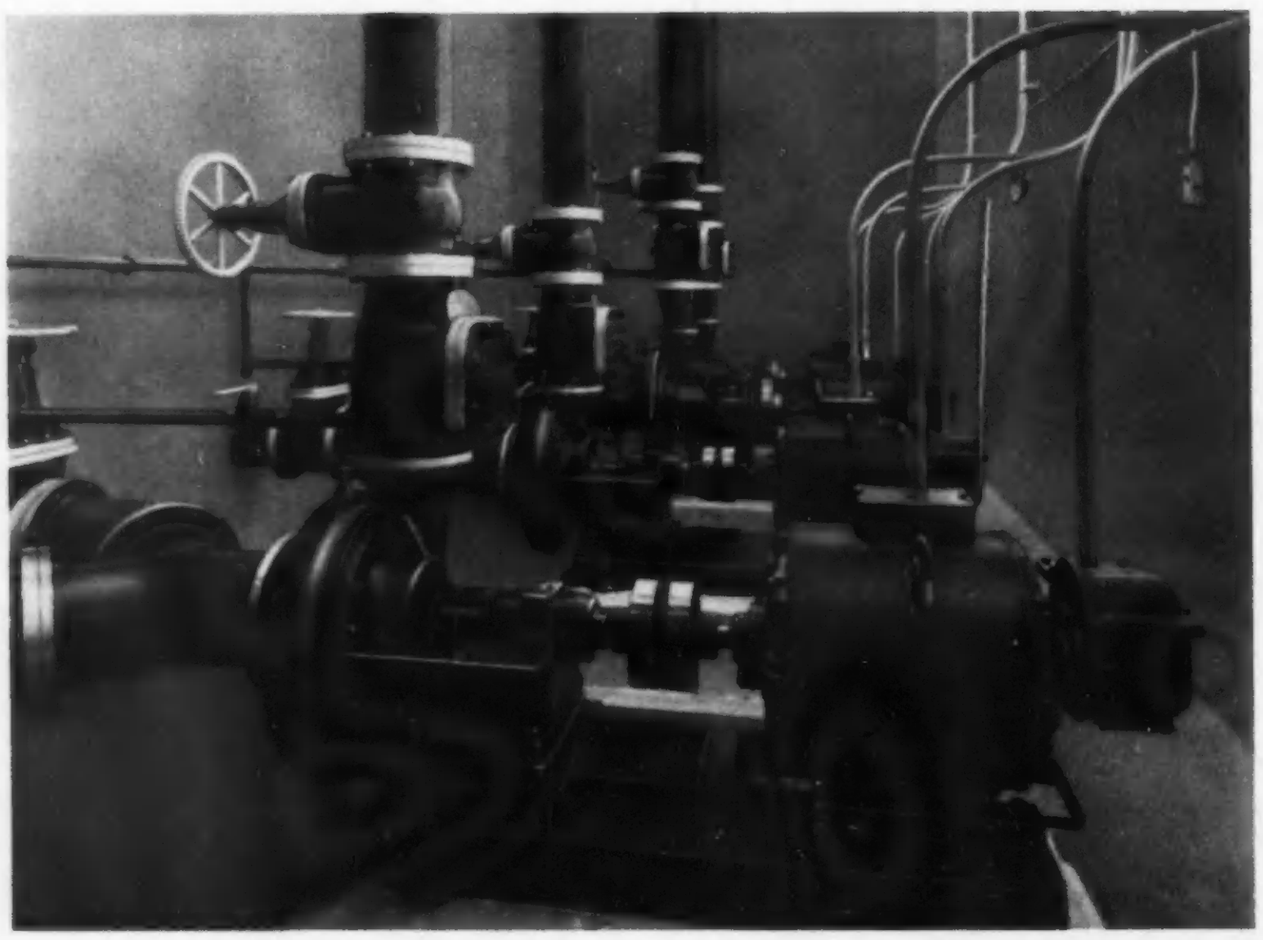
One form of relay depends for its operation on the deflection of a bi-metallic strip when heated. The movement of the strip operates contacts through a suitable mechanism to give quick make and break action. As the rectifier cools down the breaking of the contacts is delayed until a temperature is reached which is considerably below that which has caused the contacts to close.

CONCLUSION.

No detailed description of a typical sequence of operation has been given as the principles employed are well known and similar to those adopted for other types of automatic substations. It must be remembered that the mercury arc rectifier is a comparatively new development and it can be confidently predicted that many simplifications will be possible in the control gear as improved designs give greater working margins.

Considerable progress has already been made in this direction and has greatly improved the performance and reliability of this class of equipment.

Hereford Sewage Pumping Plant.



Four of the five 20 h.p., 3 phase, 50 cycle, 720 r.p.m., slipring induction motors driving Pulsometer pumps in the Hereford Corporation Sewage Pumping Station, which was designed and equipped in accordance with the specification and requirements of Mr. W. McNeil Shimmin, Assoc.M.Inst.C.E., City Surveyor to Hereford Corporation.

The Theory and Specification of Opal Diffusing Glasses.

PART II.

By J. W. RYDE, B. S. COOPER and W. A. R. STOYLE.
Research Laboratories of The General Electric Co. Ltd., Wembley, England.

Part I *of this article, which appeared in the May issue of the "G.E.C. Journal," dealt with the theory of the diffusion of light by turbid media.*

In Part II, *the three fundamental glass constants* μ, q *and NB are discussed fully and a description is given of methods for measuring the photometric quantities from which the constants can easily be determined. It is then shown how a figure of merit, assessing the relative suitability of different opal glasses, may be obtained. Finally, a method of specifying the intrinsic efficiency of opal glassware to be used in lighting fittings is outlined.*

(8) INTRODUCTION.

A RÉSUMÉ of the theoretical work on opal glasses, together with a more detailed account of certain of its practical aspects, has been given in Part I of this paper. Here it is proposed to deal, first with the methods of measurement used in the experimental work and the results obtained, and second with certain proposals for the establishment of a figure of merit for opal glasses. Finally, the application of these results to the more recent work of the British Standards Institution Sub-Committee on Diffusing Materials will be briefly reviewed.

(9) THE DETERMINATION OF THE SCATTERING COEFFICIENT q.

The determination of the constant q can only be made on a specimen that transmits an appreciable fraction of unscattered light, that is, such that a distant source, for example, the filament of a gasfilled lamp, can be seen through it. If the specimen available is too thick, it must be ground down to a sufficiently small thickness and then repolished.

The specimen is held at some distance from a small bright source of light, rendered approximately monochromatic by means of a filter, and β, the ratio of the brightness of the source, as seen through the specimen, to its actual brightness, is determined. White light must not be used in this measurement, since, in general, q varies rapidly with wavelength. The distance of the specimen from the light-source must be sufficiently great for the brightness of the surrounding field, due to transmitted scattered light, to be negligible compared with that of the source as seen through the specimen.

The value of β may be determined directly by comparing the brightness of the source, as seen through the specimen, with that observed through a calibrated neutral wedge, or a series of calibrated neutral filters. By changing the monochromatic filter in front of the source, β may readily be obtained as a function of the wavelength of the light.

Alternatively, β may be determined by a spectro-photometric method, but in this case a correction must be made to allow for the forward component of the scattered light which will be superimposed on the beam of strictly unscattered light.

From equation (1) it can be seen that

$$q = \frac{2.3}{X} \log_{10} \frac{0.92}{\beta} \qquad (7)$$

so that, if β is known for a certain wavelength, and X is measured directly from the specimen, then q may be determined. The value of q which is required is that corresponding to the wavelength, or equivalent wavelength, for which the constants α and NB are determined, in this case, 5.7×10^{-5} cms. Accordingly β should either be determined directly at this wavelength, or obtained by interpolation from values at a series of different wavelengths.

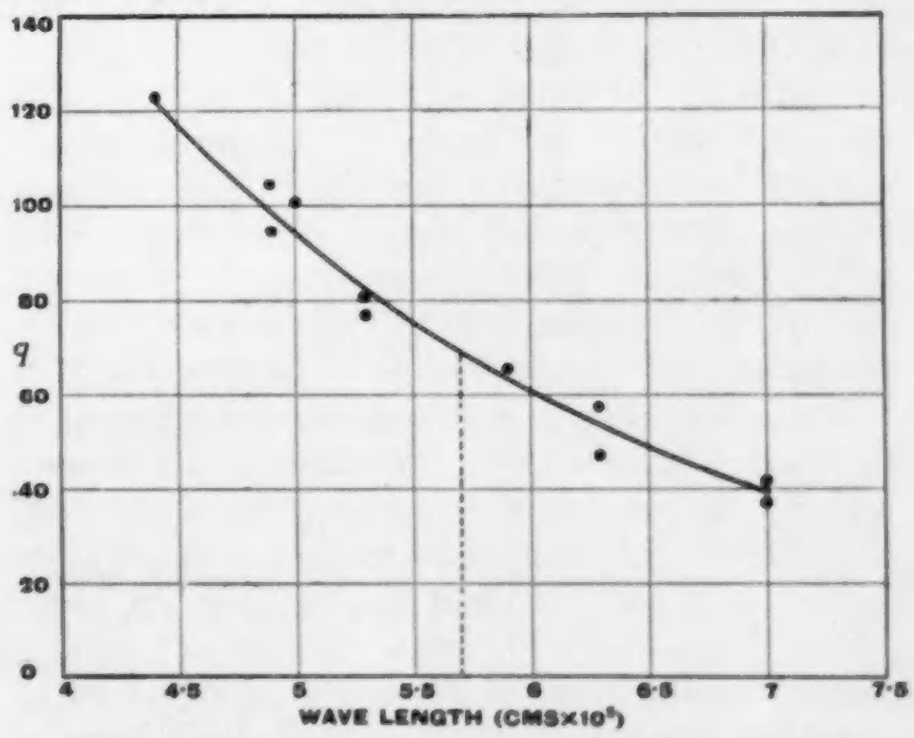


Fig. 5.—Variation of q with wavelength ; glass M.

Fig. 5 shows the variation of q with wavelength for one of the opal glasses measured. A curve has

been drawn through the experimental points, and it can be seen that the value of q for this glass, at a wavelength of 5.7×10^{-5} cms., may be taken as equal to 70.

The above fundamental methods of obtaining q are somewhat elaborate, but the following simple substitution method may be used in practice whenever a number of glasses are to be measured.

A sheet of some opal glass, known to be fairly uniform in quality, is selected and ground into the form of a wedge about 5 cms. long and then polished. The thickness should diminish uniformly from about 2 mm. to zero, and the type of glass chosen should be of a relatively lightly diffusing variety, so that the filament of a distant gasfilled lamp is only just indistinguishable through the thickest part of the wedge. By means of one of the above methods, the value of q for the glass composing the wedge is determined. Of course, this should be independent of the thickness, but in case there may be any variation in the quality of the glass from one end to the other, q may be found for different positions and a calibration curve plotted. It is probable, however, that, if the glass has been chosen carefully, the variations can be neglected. This fundamental value of q is to be found for the desired standard equivalent wavelength.

When the value of q is required for a sample of any other glass, the given specimen is, if necessary, ground down and repolished to a suitable thickness. A position is then found on the wedge such that the filament of a distant lamp appears equally bright when viewed through either the wedge or the sample. Under these conditions, the values of qX are equal. But since the thickness of the sample and that of the wedge at the above point are known, as is also the value of q for the wedge, the unknown q for the sample follows immediately, and will refer to the effective wavelength, stated above, for which the wedge was calibrated.

The above comparison can, in practice, generally be made without using colour filters, since the change in the colour of the source produced by different glasses, having the same value of qX, is usually very nearly the same.

(10) THE MEASUREMENT OF THE TOTAL TRANSMISSION FACTOR AND THE REFLECTION FACTOR OF A FLAT SAMPLE.

The determination of τ' and ρ', the total transmission and reflection factors, is made from measurements on small circular specimens cut from the glass under investigation, the specimens being ground down to parallel-sided discs of suitable thickness and then polished.

The apparatus used[13] for the measurement of these factors consists of a small integrating photometer comprising, first, an optical system giving a parallel beam of light of variable cross-section and intensity, and, second, an integrating sphere having two apertures and also a removable section of sphere wall diametrically opposite to one of them. Fig. 6 shows the apparatus set up ready for use.

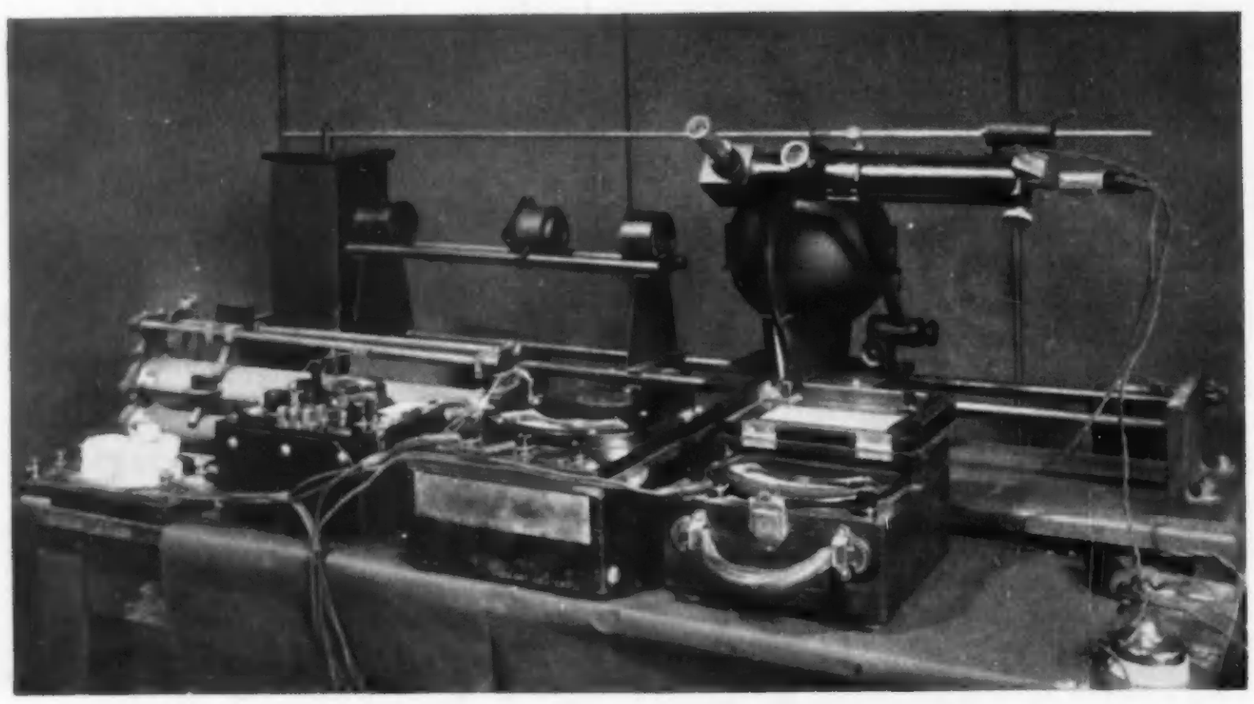


Fig. 6.—Apparatus for measuring τ' and ρ'.

As mentioned in Part I, the transmission and reflection factors depend on whether the incident light is parallel or diffuse. In the present simplified method of applying the theory, only the more easily determined pair of values τ' and ρ', which refer to parallel incident light, need be known.

(i) *Measurement of the Total Transmission Factor* τ'.

A parallel beam of light is projected through the aperture A into the sphere (see fig. 7). The brightness of the sphere wall is measured by means of a photometer viewing a point C through the second aperture D. The specimen is then inserted in the aperture A, and the brightness of the sphere wall at C again determined. A screen E, interposed between the specimen and the point C, prevents light from the specimen reaching C without at least one reflection from the sphere wall. The ratio of the second brightness measurement to the first gives the value of the total transmission factor τ'.

(ii) *Measurement of the Reflection Factor* ρ'.

As in the first experiment, a parallel beam of light is projected through the aperture A, and the brightness of the sphere wall measured. The specimen is now substituted for the removable section of sphere wall B, and the screen E transferred so that it occupies a position so as to screen C from B. A second brightness measurement is now made. The ratio of the second measurement to the first gives the value of the reflection factor ρ'.

With cased and flashed opals, accurate values of

the constants can be obtained only by using samples from which the clear glass portion has been ground away. Such a method is usually impracticable, but we have found that sufficiently accurate values of the constants for the opal glass may be determined by measuring τ' and ρ' on a sample composed of both clear and opal layers. It should be noted that the value of X to be used, when applying the curves, is the thickness of the opal glass layer alone, and not the total thickness of the sample. The most accurate values of the constants are obtained when ρ' is measured with the sample so arranged that the layer of opal glass is towards the incident light. When measuring τ', it is immaterial which way round the sample is placed.

It is particularly important that, in the determination of ρ', the specimen under test should not be mounted absolutely at right angles to the incident beam. This will ensure that light which is reflected specularly from the polished surface of the glass specimen does not emerge from the aperture through which the light enters.

In the more usual form of this apparatus, as employed by a number of other investigators,[14, 15] the specular reflection from the surface of the glass emerges through an aperture in the integrating sphere. Similarly in the transmission test, the light transmitted unscattered emerges from the integrator through another aperture diametrically opposite to the specimen. In the present work, however, the equations on which the curves in Part I have been based include the specularly reflected and unscattered transmitted light. Thus it is essential that the apparatus should be so designed as to include these quantities in the measurements.

There is one further point that may be mentioned here. It has been pointed out[16, 17] that certain errors are introduced in the measurement of τ' and ρ', when using this type of apparatus, by the necessary alteration in the conditions inside the sphere due to the introduction of specimens into the apertures. This error is a function of the relative dimensions of the apertures and the whole sphere, and also of the reflection factor of the sphere wall coating.* We have found that in the particular apparatus used, the reflection factor of the sphere coating and the size of the apertures are such that these errors are very small, and do not materially affect the values of the optical constants obtained from the photometric measurements.

The experimental details involved in measurements using this apparatus, and the conditions which have to be fulfilled in order to obtain reliable results, are given in the paper by Waldram,[13] reference to which has previously been made.

* This error becomes very large as the reflection factor of the sphere wall coating approaches unity, and also as the area of the aperture becomes an appreciable fraction of that of the sphere surface.

Having now measured the values of τ' and ρ' for the specimen, its thickness X is determined ; then the constants μ and NB for the glass may be found by using the curves given in Part I. Since, with change of wavelength, the variation in the values of μ and NB is small, the measurement of τ' and ρ' may be made using the light from a gasfilled electric lamp, for example ; the values so obtained may then be taken to refer to the equivalent wavelength of 5.7×10^{-5} cms.

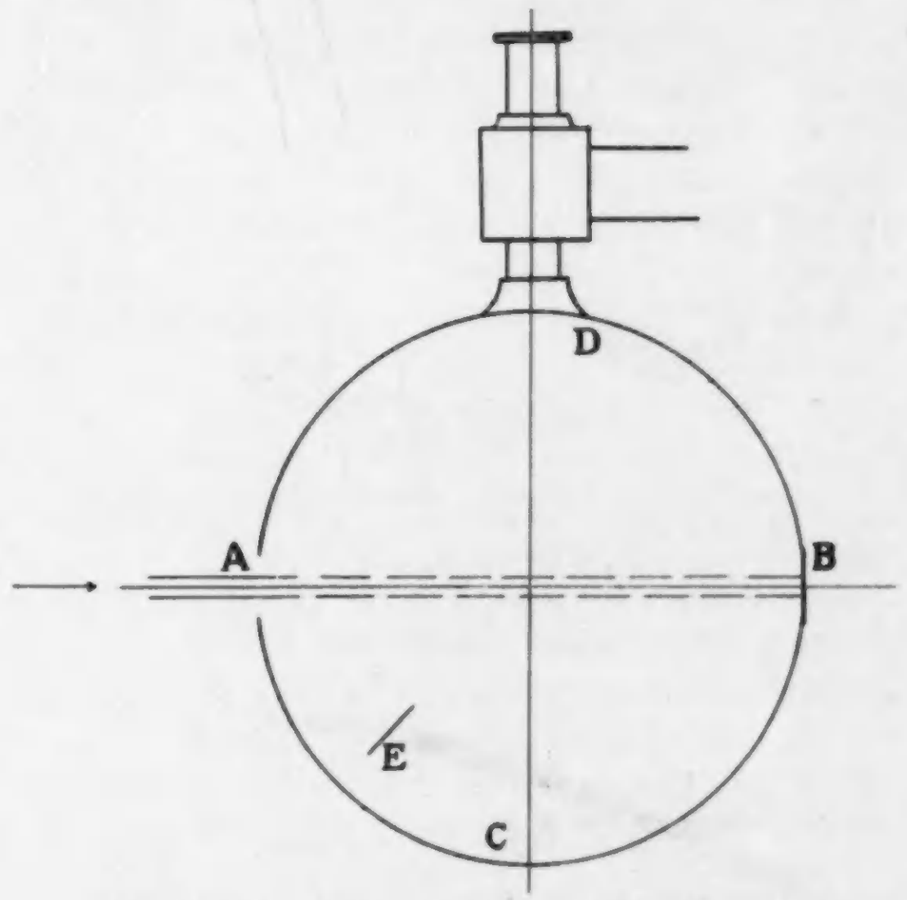


Fig. 7.—Showing arrangement of sphere for measurement of transmission factor.

(11) THE DETERMINATION OF THE MEAN WALL THICKNESS OF A GLOBE.

For some purposes we need to know the mean wall thickness of the glassware of a fitting. A very simple method of determining this is as follows. We have found from numerous tests that the density of most opal glasses is, quite closely, 2.5 grams per c.c. Assuming this value, it is then only necessary to weigh the globe and to find its surface area. The latter can be obtained in various ways, directly from measurements, for example. The mean thickness X is then given by

$$X = \frac{0.4w}{A} \qquad (8)$$

where w is the weight in grams and A is the surface area in square centimetres.

It will be realized that it is only necessary to determine the surface area of a given type of globe once and for all ; the mean thicknesses of all similar globes can then be found immediately from their weights.

As a check on this method, certain opal fittings were cut into sections, and the mean thickness directly determined for each by making a large number of micrometer measurements along the edges of the sections. Values of X obtained in this

way were found to be in close agreement with those obtained by the above simple method.

A section of a typical globe, suitable for a 100-watt lamp, is shown in fig. 8. It will be seen from this that the thickness varies from 0.138 to 0.352 cms.

(12) THE GLASS CONSTANTS.

The following table gives, for a number of glasses, the values of the three constants μ, NB and

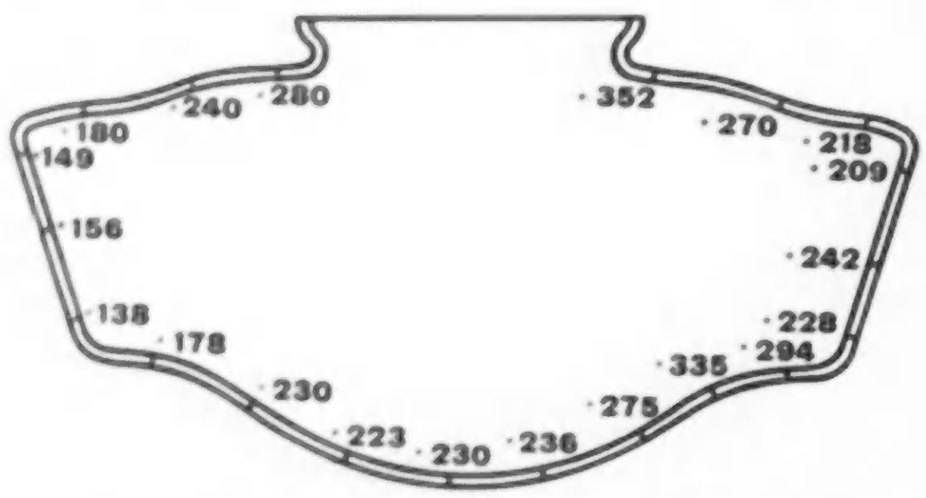


Fig. 8.—Section of 30-cm. diameter globe, suitable for 100 watt lamp. The thickness at various points is given in cms.

q, which have been determined in the manner described above.

Table III.

Glass Constants referred to an equivalent wavelength of 5.7 × 10⁻⁵ cms.

Glass	μ	NB	q
A	0.18	5.3	230
B	0.25	4.5	130
C	0.21	7.4	80
D	0.20	6.0	110
F	0.37	1.05	28
G	0.44	0.55	18
H	0.13	10.8	230
J	0.18	6.2	230
K	0.40	14.8	120
L	0.62	32.0	195
M	0.21	3.6	70
N (flashed)	1.1	30.0	1400
P (cased)	0.36	7.3	160

With few exceptions, notably N and P, which are flashed and cased opals respectively, the glasses referred to in the table are ordinary pot opals. All except L, which is many years old, are of comparatively recent manufacture.

As regards the variation of the constants corresponding to different batches of the same type of glass, made at different times, we have generally observed that these are fairly small. This may be illustrated by Table IV which shows the values obtained from tests made on deliveries, from one manufacturer, extending over a period of about 12 months. As a matter of fact, the variations over samples taken from the same batch are often nearly as great as those found in different batches. Changes of this order of magnitude are, in general, quite unimportant.

Table IV.

Test	μ	NB	q
1	.19	6.6	80 to 100
2	.21	7.2	
3	.17	6.7	
4	.20	6.0	

Quite apart from the use of the constants to calculate the various optical properties corresponding to different thicknesses of the glasses, a considerable amount of other information concerning the intrinsic qualities of the opals themselves can be derived from μ, NB and q. It is hoped that this information will be of value to the manufacturer, especially when the conditions controlling the size and number of the particles which separate out become more fully understood.

The constant μ, it will be remembered, is an absorption coefficient, so that glasses having a high value of μ will absorb more useful light than those having lower values. Our experience indicates that, to be efficient, pot and cased opal glasses for use in lighting fittings should certainly not have a value of μ in excess of 0.25. Typical glasses which are unsatisfactory in this respect are K, G and L. The importance of a low value of this constant may be seen from fig. 3a, which shows how, for a given thickness, the value of σ and therefore of the light output ratio of a globe decreases as μ increases. We have seen that, in opal glassware, much of the incident light has to travel backwards and forwards through the glass before emerging. It follows from this that the reduction in transmission, due to the presence of a given amount of absorbing material, will be much greater from an opal than from a clear glass. If, therefore, a manufacturer finds that the value of μ is high for an otherwise good glass, he should make every effort to reduce the amount of absorbing material, such as iron, which may be present. The addition of manganese as a decolourizer will, of course, only make matters worse.

Now let us turn to the remaining constants q and NB, which are both directly related to the particles present in the glass. It is of interest to note that the ratio q/NB will remain constant when we alter the number but not the size of the particles. This is because both constants vary in direct proportion to the number present per unit volume. On the other hand, any change in the size of the particles will occasion a corresponding change in the ratio q/NB. The relation between this ratio and particle diameter has been fully worked out for spherical particles[9], but we shall not stop to discuss this here. As a very rough rule it may be said that according as this ratio is greater or less than 12 so will the average particle diameter be above or below one thousandth of a millimeter. This assumes that the range of sizes present is not too great.

From a glance at Table III we can thus say that glasses K and L have small particles, while N and F have large ones. Thus, the value of q/NB for glass K is 8.1, and the average observed particle diameter is 0.45×10^{-3} mm., while for glass N the ratio q/NB is 46.6 and the average diameter about 4.0×10^{-3} mm.

Considering the correspondence between these constants and the optical behaviour of the glass, we may say that q is a scattering coefficient relating to the amount of light diffused by the particles in all directions, while, roughly speaking, NB is related to the amount scattered by them in backward directions only. Thus, the greater the value of q, the more completely will a given thickness of glass obscure the light-source, while the greater the value of NB, the larger will be the fraction of the incident light reflected.

The above considerations enable us to form some idea of the best values of the constants to meet various practical requirements. Thus, if we intend to use the glass as a reflector, there is no question of the light source being visible through it, so that the value of q is immaterial, but, as mentioned above, the constant NB should be as large as possible. It follows that, of the glasses in Table III, we should choose L or N for the above purpose.

To illustrate this case, Table V shows the set of glasses arranged in order of their reflection factors ρ' corresponding to sheets 0.2 cm. thick.

Table V.

Reflection and Transmission Factors, ρ' and T' for sheets of thickness 0.2 cm.

Glass	μ	NB	ρ'	T'
L	0.62	32.0	0.70	0.13
N	1.10	30.0	0.64	0.11
K	0.40	14.8	0.62	0.26
H	0.13	10.8	0.61	0.35
C	0.21	7.4	0.53	0.40
P	0.36	7.3	0.51	0.38
J	0.18	6.2	0.51	0.44
D	0.20	6.0	0.50	0.44
A	0.18	5.3	0.48	0.46
B	0.25	4.5	0.45	0.48
M	0.21	3.6	0.42	0.51
F	0.37	1.05	0.29	0.59
G	0.44	0.55	0.24	0.62

It will be seen from this table that, in a general way, for thicknesses such as this, the order of the glasses is the same for ρ' as for NB. Such a statement is, however, not strictly true because it leaves out of account the effect of μ. The influence of this constant is not great in this case, but it may reverse the order of two glasses having nearly equal values of NB.

From the last column of the table we see that much the same applies to the transmission factor τ', except that now the values are in the reverse order. The action of μ is here slightly more important, and it has upset the regular order in the case of glasses C and P, for example.

Of course, the best transmission will be obtained when NB is zero; in other words, when there are no particles there at all! In practice, however, we generally need the diffusion of the light to be as complete as possible, and to assess this we must bring in the value of q. To do this $(qX)_v$ must be calculated; the suitable equation similar to (2), Part I, has already been given.[12] We shall not, however, develop this point further, as much the same conditions occur in the next problem we have to consider.

The case of globes, when the condition is laid down that the light-source is not to be visible, is perhaps of even more general interest. If, in making the glass, we had complete control over the size and number of the particles, we should proceed as follows:—

In the first place, we must naturally reduce μ as much as possible. But since, in spite of all precautions, there will always be some absorbing material present, it follows that, for maximum transmission, the globe should be blown as thin as its mechanical strength will safely allow, and then the diffusing power increased until the source is just obscured. Next, it is easy to see that NB must be low, since otherwise the reflection factor of the glass will be high and much of the light from the lamp will be reflected back into the interior of the globe instead of being transmitted directly. Hence we must adjust the value of q to the minimum value necessary to obscure the light-source and, at the same time, make NB as low as is consistent with this.

Now we have seen that the ratio q/NB increases with particle size, so that, to make NB small for a given value of q, we must have large particles. In our experience they should be not less than one or two thousandths of a millimetre in diameter.*

To sum up, the optimum conditions are thus:—

(1) Wall thickness as small as is practicable.

(2) Impurities causing absorption to be reduced to a minimum.

(3) The value of q must be near to that corresponding to $(qX_v)/X_o$ where the numerator is given by equation (3) and X_o is the smallest thickness likely to occur anywhere on the globe.

(4) The value of NB must be as low as is consistent with (3). That is, the particles should be large.

(5) Or, to express (q) in another way, the ratio q/NB should be large—greater than 15, for instance.

A glance at Table III shows at once that glass L is quite unsuitable for globes, since $\mu = 0.62$ and also

*There does not seem to be much advantage to be gained by going to diameters distinctly greater than this. The theory indicates that the additional gain is small and in practice it seems difficult to get much larger particles without also forming a quantity of very small ones.

q/NB is only 6.1. On the other hand, glasses A and J are very good, since their μ values are very low and q/NB is high.

The conditions which we have just established are useful as showing what values of the constants are to be aimed at. If, however, we wish to decide on the relative suitability of a large number of glasses, the values of the constants themselves will only serve as a basis for a very broad classification into good, bad and indifferent types.

The reason is that there are three constants concerned, and it is often impossible to see at a glance just what their combined effect on the performance of the glass will be. In order to overcome this difficulty a scheme was devised[12] whereby a single figure of merit for each glass could be determined; this then allows any number of glasses to be compared and arranged in order of their suitability. We shall discuss this in the following section.

(13) THE FIGURE OF MERIT OF DIFFUSING GLASSES TO BE USED FOR GLOBES.

We cannot assess the relative suitability of various glasses (to be used in the form of globes for lighting fittings) by knowing only the light output ratio of a sample fitting of each type. A globe of a really good glass may have been blown with too great a wall thickness while another, giving a very high light output ratio, may not adequately obscure the light-source. Again, the particular canopy used will affect the results.

In order to overcome these difficulties we propose to take as the figure of merit the value of σ corresponding to the particular wall thickness most suitable for each glass; provided that this thickness is not less than that consistent with adequate mechanical strength.

It will be remembered that σ is the transmission factor for a complete spherical globe enclosing the light-source and that, if the glass constants are known, its value can be determined immediately from the curves given in fig. 3.

The figure of merit f of a glass, to be employed as a globe in lighting fittings, will be defined as the value of σ corresponding to the least wall thickness which will completely obscure the light-source and at the same time give adequate strength. Let X_v be the thickness which only just prevents the source being seen through the glass and X_o the minimum thickness to give sufficient strength.[12] Then we can say more briefly that the figure of merit f is the value of σ determined for a thickness equal to whichever is the greater of X_v and X_o.

Strictly, of course, this means that the figure of merit will depend upon the size and shape of the globe and on the type of lamp with which it is intended to be used. We have already seen that changes in shape do not affect σ to any great extent, so that this factor can be neglected for our present purpose. With electric lamps, equation (3) shows that the value of $(qX)_v$ varies very little for the various pairs of values of wattage and globe diameter used in practice. This is because for larger lamps correspondingly bigger globes are used, so that $\log (d^2/W)$ changes very slightly. In the present case it will therefore be sufficient to take $(qX)_v = 12.8$. The same arguments will apply to other illuminants, but, for these, new values of $(qX)_v$ must be determined. The value of X_v is obtained immediately from $(qX)_v$ by dividing this by the constant q for the glass.

Now as regards X_o, measurements which we have made on a large number of fittings show (see next section) that the minimum mean wall thickness necessary to give adequate strength is about 0.13 cm., so that we shall adopt this value.

As an example, we shall find the figure of merit for glass A. Since, from Table III, $q = 230$, we obtain $X_v = 0.056$ cm. Then, since this is less than the fixed value of $X_o = 0.13$ cm., we determine σ, for a thickness equal to X_o, by fig. 3. The value comes out to be 0.935, and is the required figure of merit.

Again, in the case of glass C, $q = 80$, so that $X_v = 0.16$, which is greater than X_o. In this case, therefore, f is given by the value of σ corresponding to a thickness of 0.16 cm.

The values of f, obtained in the above manner, for all the pot-opal glasses are given in the following table :—

Table VI.

Figure of Merit for Pot Opal Glasses

$X_o = 0.13$ cm. $(qX)_v = 12.8$

Glass	q	X_v cms.	μ	NB	Thickness at which f is calculated	Figure of Merit f
A	230	0.056	0.18	5.3	X_o	0.935
B	130	0.099	0.25	4.5	X_o	0.915
C	80	0.160	0.21	7.4	X_v	0.89
D	110	0.117	0.20	6.0	X_o	0.925
F	28	0.46	0.37	1.05	X_v	0.67
G	18	0.71	0.44	0.55	X_v	0.50
H	230	0.056	0.13	10.8	X_o	0.945
J	230	0.056	0.18	6.2	X_o	0.93
K	120	0.107	0.40	14.8	X_o	0.82
L	195	0.066	0.62	32.0	X_o	0.64
M	70	0.183	0.21	3.6	X_v	0.895

It will be seen that glasses A, F, H and J have an exceptionally high figure of merit and thus are the most suitable. In fact, it might well be laid down by the user that the glass must have a figure of merit greater than, say 0.90. It will be noted that all the glasses whose f is greater than this have a low value of μ.

So far we have only considered pot opal glasses but, with a few simple modifications, the figure of merit can, in addition, be found for flashed and cased opals and also for those having matt surface finishes; the method is thus quite general.

In the case of flashed and cased opals, the question of a minimum thickness to give adequate strength does not concern us, so that X_0 must now refer to the minimum thickness of flashing that can be satisfactorily produced. We have not yet sufficient data to lay down this figure but, once it is established, the procedure to find f is the same as that already given for pot opals. Sufficiently accurate values of the constants for this purpose may be determined by the method described in Section 10, but it should be remembered, when using figs. 2 and 3, that X now refers to the thickness of the opal layer and not to the total thickness of glass.

When either the internal or external surface of the globe is treated to produce an etched or other type of matt finish, the question of filament visibility hardly arises. It follows that, in this case, the optimum performance will be obtained when the thickness is equal to the appropriate value of X_0, so that the figure of merit will always be the value of σ corresponding to this thickness. The glass constants should always refer to the opal glass itself and they should be determined from measurement on a sample having the light incident on the polished surface. We have shown that under this condition, fig. 3 may still be used to find the constants and then the value of f. It may be noted that, in this particular case, a determination of q will not be necessary.

(14) A PROPOSED METHOD FOR THE SPECIFICATION OF OPAL GLASSWARE FOR LIGHTING FITTINGS.

In August, 1929, and January, 1931, reports on our theory were presented to the British Standards Institution Sub-Committee dealing with Diffusing Materials. Since, at this time, the existing British Standard Specification on Translucent Glassware Illumination Fittings[18] was under revision, it was thought that it might be possible to amplify this specification in the light of some of the results obtained during the course of the work described above.

The only reference in the existing specification to the performance of a fitting is in Clause 11, which says that the efficiency shall be stated by the maker, and the actual efficiency shall not differ from this by more than $\pm$ 15 per cent of the stated value. Thus there is no check on the quality of the product produced, but only on its limits of variation.

This was not at all adequate, and the first suggestion that was considered was that the quality of the actual glass used (as defined in some manner by the values of its optical constants) might be specified.

A lower limit for the figure of merit, for example, might be laid down, but this needs somewhat lengthy measurements, and probably would entail the destruction of the fitting. This method is thus impracticable. The use of the figure of merit is, of course, valuable for selecting the most suitable out of a number of types of glasses which might be used for a given purpose, but it was clear that it could not form the basis of a simple specification.

All opal fittings of necessity occasion a certain loss of light and the value of the specification to the user is to ensure that this loss shall not be unnecessarily high. It follows that the specification should state a lower limit for the light-output ratio of the fitting; but clearly this must be measured under some standard conditions. It will be seen, moreover, that this alone is not sufficient, because the manufacturer of a bad glass has only to blow his globes sufficiently thin in order to raise their efficiency above the limit proposed. The fittings would then be unsatisfactory on account of fragility. Again, even if they were strong, they would probably allow the filament of the lamp used to be seen. We thus arrive at the necessary conditions.

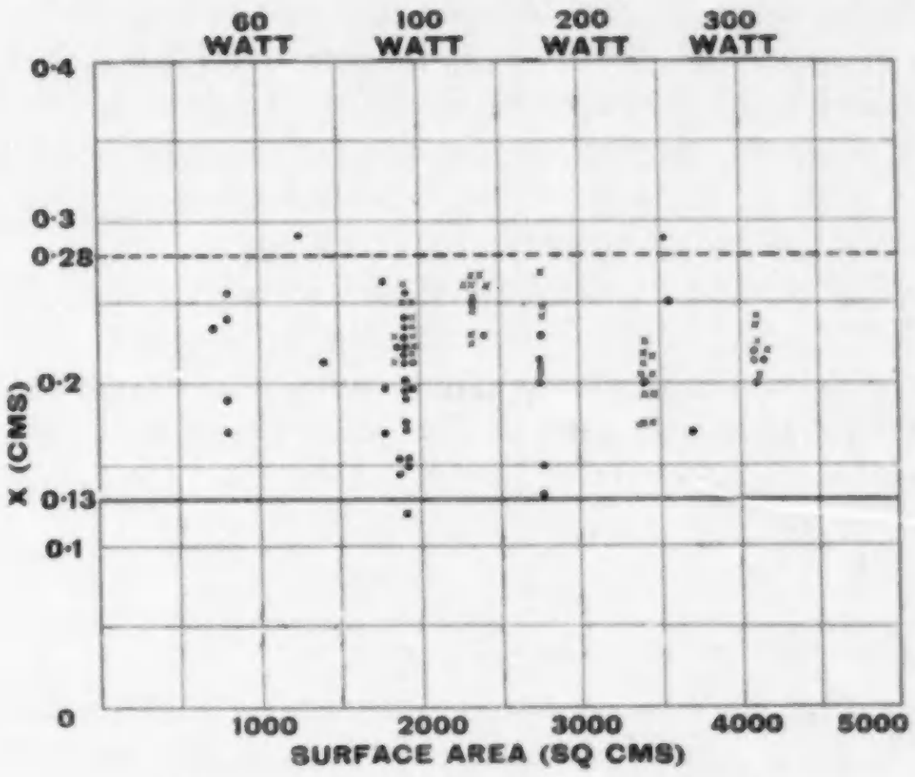


Fig. 9.—Mean thickness of glassware.

• Glassware of very recent manufacture.
• Representative samples collected over a period of several years, including a certain number of uncommon forms.

(1) The efficiency, when measured in a specified manner, must be greater than a given value.
(2) The thickness must not be less than a certain minimum.
(3) The light-source must not be visible through the globe.

As soon as it was attempted to define these conditions more fully and to fix the limits, it was realized that the matter was by no means as simple as it appears at first sight. It will be seen that if one universal lower limit for efficiency were laid down for all types of fitting, it would have to be fixed at a low value in order to include the types whose form is such as necessarily to lead to poorer efficiencies. But this limit would not then keep up the standard of the intrinsically more efficient types. It also appeared at first sight as if the lower limit of thickness would be dependent on the size and nature of the fitting.

The basic proposal seemed to be sound, but it was quite clear that a considerable amount of work would have to be done before a simple form of specification could be evolved. This work we undertook to carry out, and the results showed that several simplifications could be made, which were not apparent when the problem was first attacked.

It was decided first to investigate the variation of mean wall thickness with size and type of fitting. The results are shown in fig. 9, where the thickness of the globes is plotted against the surface area. About eighty fittings were measured, their diameters ranging between 15 and 40 centimetres. The globes included specimens of about 14 different types, both of British and foreign manufacture, and were chosen to be as representative as possible.

From these results the important facts emerged that the average mean thickness of any type of fitting is practically independent of the size while, for almost all the fittings, the mean thickness was found to lie between the limits 0.13 and 0.28 cms. It appears, therefore, that it will not be unreasonable to take 0.13 as the required lower limit of mean thickness for all normal sizes of fitting.

Remembering the method, described in section 11, for finding the mean thickness, we see that the minimum thickness clause can now be put in the following simple form: The mean thickness of the glassware, determined by the following formula—

$$0.4 \times \frac{\text{weight of globe in grams}}{\text{surface area in sq. cms.}}$$

shall not be less than 1.3 mm.

The question now arises as to how to determine the lower limit of light-output ratio to be specified. This cannot be done by measuring its value for a large number of representative fittings and then deciding on an arbitrary minimum value for acceptance. There are several reasons for this. First, unless due allowance were made for the effect of different types of canopy, this would be no criterion of the performance of the globes themselves. Some standard method of measurement, which would eliminate the effect of the canopy, would therefore have to be laid down. Second, even with such a system, there would still be the difficulty due to the fact that some forms of globe, for example, those with large apertures are bound to give a relatively low value of the light-output ratio. A limit imposed to allow for these would be unnecessarily lax for those with small apertures.

It was realized that both of these difficulties could be eliminated if, instead of trying to fix a universal minimum of the light-output ratio, we made this restriction apply to σ. This latter, it will be remembered, is the ideal light-output ratio which would be obtained if the globe were without apertures, spherical in shape and of uniform wall thickness.

We have already shown in Part I, Section 7, that there is a simple relation between σ and η_0 the light-output ratio measured under certain easily realizable conditions, which do not differ greatly from those obtaining in actual use. Thus, once a universally applicable lower limit to σ has been laid down, corresponding limits of η_0 for all the various cases can immediately be calculated by equation (6), if the size of the aperture and the reflection factor r of the card placed over it are known, together with the value of ρ' for the glass.

The necessity of knowing ρ' and r makes this step inconvenient for specification purposes, but further work has shown how the difficulty may be overcome. The essential advance was made by realizing that if we lay down the condition that η_0 is to be measured with the aperture covered by a white plate or card of high reflection factor, likely variations in ρ' become unimportant.

Hence, if we specify the reflection factor of the card, the necessity for any calculation is obviated, since a small table can be drawn up giving the relation between η_0, measured under the above condition, and θ the plane angle subtended by the aperture at the light-source.

By this procedure we secure another most important advantage. This is that the error in the measurement of η_0, due to any slight variations in the position of the light-source, is less the higher the reflection factor of the card covering the aperture. Thus, with a black cover, a change of 1 in. in the distance of the lamp filament from the aperture produced a change in η_0 from 0.67 to 0.73, while, with a white card of reflection factor of 0.8, a similar change in distance only altered the value of η_0 from 0.845 to 0.85.

The actual values of the limits were fixed in the following way: The constants μ and NB were determined for a large number of representative glasses and, by means of these, curves connecting σ with wall thicknesses were determined. The results are shown in fig. 10. Curves representing good modern glassware, produced by a number of makers, all fall close together towards the top of the diagram. Of the curves falling below these, some are of quite recent manufacture, and others represent the production of some few years ago. The lettering corresponds with Table III, which gives the glass constants.

After careful consideration it was decided that a suitable minimum value of σ would be 0.825, since curves for all the "good" glasses lie above this value over the whole of the practical range of wall thicknesses. This does not reject all the other glasses entirely, since, as will be seen from the figure, a globe made from glass B, for example, will be satisfactory in respect of its light-output ratio, provided that its wall thickness is less than 0.24 cm.

We now need to choose the value of the reflection factor r of the card to be used over the aperture when measuring η_o. For the reasons already given, the value of r should be greater than 0.7, say. Now "Bristol board" is a convenient and accessible material, and measurements showed that its reflection factor, when clean, is round about 0.80. The standard reflection factor for the aperture card was fixed at this value, so that for all but critical tests, "Bristol board" may be employed.

Having fixed the lower limit of σ and the value of r, the corresponding lower limits of η_o, for various values of θ and ρ', can now be deduced from equation (6). The results are given in Table VII for three values of ρ' covering the likely range.

Table VII.

Values of η_o for $r = 0.80$

θ	Values of η_o for a representative range of glasses			Mean values of η_o
	$\tau' = 0.35$ $\rho' = 0.578$	$\tau' = 0.45$ $\rho' = 0.458$	$\tau' = 0.55$ $\rho' = 0.337$	
0°	0.825	0.825	0.825	0.825
20°	0.824	0.824	0.824	0.824
40°	0.813	0.814	0.816	0.814
60°	0.795	0.802	0.806	0.801
80°	0.777	0.788	0.793	0.786
100°	0.747	0.764	0.773	0.761
120°	0.708	0.733	0.747	0.729

(Practical Range)

The values of η_o for this range of ρ' are now seen not to differ greatly from the mean values given in the last column of the table. It appears, therefore, that the measurement of ρ' in each case is unnecessary, so that the lower limits of η_o, corresponding to the fixed values of σ and r, can be obtained directly from the following simple table :—

Fig. 10.—Curves relating to σ to wall thickness for globes of various glasses.

Table VIII.

Angle subtended by the diameter of the opening at the light - source, when in its correct position.	Light-output ratio to be greater than the figures given below when the opening is covered with a flat sheet of an opaque material whose diffuse reflection factor is not greater than 0.8
0°	0.825
20°	0.82
40°	0.81
60°	0.80
80°	0.78
100°	0.76
120°	0.73

A little consideration will show that this same table is also applicable to both flashed and cased opal glasses.

The efficiency clause can now take the very simple form :—

> The light-output ratio of the glassware, when measured in the specified manner, shall be in accordance with Table VIII.

The "specified manner" referred to means that the reflection factor of the card covering the aperture of the globe shall not be greater than 0.80; also that the source of light shall be an uncapped electric lamp, suspended by fine wires, so as to occupy the normal position of the lamp employed in practice.

It will be seen that if, at any future date, it is thought desirable to stiffen a specification of this type, all that need be done is to decide on a new value of σ from which the corresponding values of η_0 for Table VIII immediately follow.

Finally, to complete the set of clauses involving the optical qualities of the glass, it is only necessary to add one more to the effect that the light-source shall not be visible through the globe.

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